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SHREDDED RUBBER TIRES AS A BULKING AGENT FOR COMPOSTING SEWAGE SLUDGE

by

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16. ABSTRACT

Shredded rubber tires were evaluated as a bulking agent for composting wastewater sludges. Three sludges (raw primary, anaerobically digested, and secondary biological), two amendments (sawdust and recycled compost), three sizes of rubber chips (1.27 to 2.54 cm, 2.54 to 5.08 cm, and greater than 5.08 cm), and three shredded-rubber-chipto-sludge mix ratios (1:1, 2:1, and 3:1) were evaluated. The small rubber chips, the 2:1 mix ratio, and the sawdust amendment were optimums.

Tests with raw primary sludge, shredded rubber, and no amendments resulted undesirable odors and handling difficulties. A high moisture content and low C/N ratio led to sludge balling, anaerobic conditions, and the production of ammonia gas. Tests with all three sludges and recycled compost produced similar results.

When amended with sawdust, all of the sludges were effectively composted using shredded rubber. All of the sludges required the moisture absorbancy and supplemental carbon that the sawdust provided.

Heavy metal levels during composting with raw primary sludge and rubber chips increased due to the concentrating effect as organic matter decomposed. In addition, the shredded rubber chips were found to contribute zinc and iron to the finished compost. Recycling the rubber chips reduced the zinc and iron levels, but they were still high after five cycles. However, the levels were not high enough to limit the use of shredded rubber in the composting of the sludge.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing muncipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researchers and the user community.

This paper relates to the EPA's Research and Development program and is concerned with the treatment and ultimate utilization of wastewater sludge.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

This study evaluated the use of shredded rubber tires as a bulking agent for static pile composting of wastewater sludges. The optimum particle size and rubber-to-sludge mix ratio for efficient composting were determined using raw primary sludge. Raw primary, anaerobically digested, and secondary biological sludges were then tested with the optimum size rubber chips and mix ratio to evaluate two amendments--sawdust and recycled compost. The contribution that the shredded rubber made to the heavy metals content of the finished compost was determined. Rubber chips were recycled to determine whether heavy metal levels would be reduced in the finished compost.

The shredded rubber was classified into three sizes 1.27 to 2.54 cm, 2.54 to 5.08 cm, and above 5.08 cm. The reduced moisture, volatile solids, and total carbon, as well as field observations indicated that the small rubber chip was optimum. Additional trials evaluated the rubber-chip-to-raw-primary-sludge mix ratios of 1:1, 2:1, and 3:1, and showed that the 2:1 mix ratio was optimum.

Composting with raw primary sludge and shredded rubber resulted in undesirable odors and handling difficulties. A high initial moisture content and low C/N ratio led to sludge balls, anaerobic conditions, and conversion of excess nitrogen to ammonia gas. The addition of recycled compost produced similar results, but the addition of sawdust produced a lower initial moisture content and an increased C/N ratio, thus eliminating odors and producing a dry, stabilized compost.

When mixed with sawdust, anaerobically digested and secondary biological sludges were effectively composted using shredded rubber chips. Because of their high moisture content and low C/N ratio, these sludges require a moisture-absorbing amendment and supplemental carbon.

Heavy metal levels increased because of the concentrating effect that occurred as organic matter decomposed. In addition, the shredded rubber chips contributed Zn and Fe to the finished compost. Although recycling of the shredded rubber chips reduced the Zn and Fe concentrations, they were still high after five cycles.

This research project successfully demonstrated the use of shredded rubber tires as a bulking agent in the composting of sewage sludge, but only when amendments were added to reduce moisture content and supply carbon. Although Zn and Fe levels were elevated, they were not high enough to limit the use of shredded rubber in the composting of sewage sludge.

This report was submitted in fulfillment of Cooperative Agreement CR810255-01 by the Rutgers University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from September 12, 1983, to February 28, 1986, and work was completed as of February 28, 1986.

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SECTION 1

INTRODUCTION

The static pile composting of sewage sludge has historically used wood chips as a bulking agent in the composting process. The bulking agent provides structure, air space, moisture absorptive capacity, and carbon if needed. However, wood chips are biodegradable and easily lost in the composting process. Sikora et al. (1) estimate that approximately 30 percent of the initial volume of wood chips is lost per composting cycle. Thus a need exists to identify recoverable, low-cost bulking agents such as shredded rubber tires.

Studies conducted at Rutgers University by Higgins et al. (2) showed that shredded rubber tires were a potential substitute for wood chips as a bulking agent. Experiments conducted using raw sludge showed that temperatures of 55°C could be developed and maintained for pathogen destruction. The results of the tests also showed that the shredded rubber contributed Fe and Zn to the finished compost and resulted in elevated levels of these constituents in the compost. Other studies conducted by Harding et al. (3) in Windsor, Ontario, also demonstrated that shredded rubber tires could be used as a partial substitute for wood chips. Their ultimate goal was to substitute two-thirds of the wood chips with shredded rubber.

OBJECTIVES

The earlier experiments conducted at Rutgers University and Windsor, Ontario, concentrated on the general acceptability of shredded rubber tires as a substitute bulking agent. Based on this experience, more definitive research was initiated with the following objectives:

1. To determine the optimum tire particle size and rubber-to-sludge mix ratio for efficient composting;

2. To evaluate the different types of sewage sludges that could be composted with shredded rubber;

3. To determine whether supplemental sources of carbon are required to enhance the composting process, particularly for biological and digested sludges with low energy values; and

4. To determine the heavy metal contribution of shredded rubber and the number of cycles required before a reduction in heavy metal levels occurs.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Three sizes of rubber chips were tested as bulking agents for raw primary sludge: 1.27 to 2.54 cm (small), 2.54 to 5.08 cm (medium), and greater than 5.08 cm (large). In addition, three rubber-chip-to-raw-primary-sludge volumetric mix ratios were evaluated: 1:1, 2:1, and 3:1. The small chip size and the 2:1 mix ratio were found to be the optimums.

Although the combination of raw primary sludge and shredded rubber produced thermophilic composting temperatures, undesirable odors and handling difficulties resulted even at the optimum rubber size and mix ratio. A high initial moisture content and sludge balling during mixing resulted in anaerobic conditions which produced the objectionable odors. In addition, a low C/N ratio resulted in the production of noticeable concentrations of ammonia gas.

Raw primary sludge mixed with sawdust and bulked with shredded rubber lowered the initial moisture content and increased the C/N ratio, thus eliminating odors and screening problems. A minimum of one part of shredded rubber chip per part of sludge is recommended to provide sufficient bulk for porosity and structure. The quantity of sawdust required depends on the moisture content and C/N ratio of the sludge. Mixtures with a moisture content of 55 to 60 percent combined with a C/N ratio of approximately 25:1 successfully eliminated odors and produced a dry, stabilized compost.

Lowering the moisture content by using recycled compost did not effectively eliminate odors and screening problems, probably because of the lack of carbon for increasing the C/N ratio. In addition, recycled compost was not totally effective in preventing the formation of sludge balls. Hence recycled compost is not recommended as an amendment in the composting of sewage sludge and shredded rubber unless it is combined with another amendment such as sawdust.

Anaerobically digested and secondary biological sludges also require the use of amendments such as sawdust to lower the initial moisture content and increase the C/N ratio. When mixed with these sludges, sawdust effectively eliminated odors, the formation of sludge balls, and screening problems and ensured composting temperatures of 55°C. Because of the low C/N ratio and high moisture content of these sludges, amendments containing available carbon are essential.

Shredded rubber chips were found to contribute zinc and iron to the compost. Repeated recycling of the rubber chips resulted in lower concentrations of these two metals in the finished compost. However, elevated

zinc levels are expected to be found in the finished compost for the life of the shredded rubber chip, since zinc oxide is part of the rubber matrix and will continue to be abraded from the surface during mechanical handling. On the other hand, iron is contributed from steel belts and rim beads and should eventually be completely oxidized and no longer contribute to the finished compost.

All heavy metals increased in concentration when only sludge and shredded rubber were composted. This result was due to the concentrating effect of organic matter decomposition. However, amendments such as sawdust will supply organic matter that will lower the heavy metals concentration in the finished compost.

Although not tested, other amendments that absorb moisture and supply carbon (e.g., shredded bark and wood chips) should effectively lower the moisture content and increase the C/N ratio to prevent odors and screening problems. The use of shredded rubber tires as a bulking agent in the composting of sewage sludge is recommended in combination with amendments such as sawdust that reduce moisture content and supply carbon. Because shredded rubber tires are not biodegradable and can be recycled, they have a distinct cost advantage over biodegradable materials which may supply carbon and absorb moisture as well as bulk. All types of dewatered sewage sludge can be composted using shredded rubber tires when adjustments for moisture content and available carbon are made. Although elevated, Zn and Fe levels do not appear to be high enough to limit the use of shredded rubber in the composting of sewage sludge.

SECTION 3

MATERIALS AND METHODS

The use of shredded rubber tires as a bulking agent for the composting of sewage sludge was investigated using replicated composting vessels. For this research project, three compost vessels were constructed of wood with dimensions of 1.83 m (6 ft) by 1.83 m (6 ft) by 1.37 m (4.5 ft) as shown in Figure 1. The vessels were insulated with styrofoam board to minimize sidewall effects. The vessels were designed with an airflow plenum placed at a height of 15.2 cm (6 in.) from the bottom for proper air distribution within the composting mass (Figure 2). The front wall of the vessel was used as a gate for unloading the composting vessel. One blower was connected to each vessel for aeration.

A drum was fixed between the composter and the blower with a 10.16 cm (4 in.) aluminum pipe. Three taps were installed in the aluminum pipe to measure the pressure drop across an orifice and the blower. The blower was controlled by a time clock and thermostat. The thermostat was set at 55°C and was located in the center of the composter. It was designed to override the time clock during peak activity periods to maintain the temperature at 55°C. During low activity periods, the time clock provided intermittent aeration to maintain aerobic conditions. At the beginning of each experiment, the minimum airflow rate was set at 31.2 cubic meters per hour per dry metric ton (m^3/hr-dmt) [1000 cubic feet per hour per dry ton (ft^3/hr-dt)]. During peak activity periods, the maximum airflow rate of the blowers was 499.4 m^3/hr-dmt (16,000 ft^3/hr-dt).

The dewatered sewage sludge for the composting experiments was obtained from three sources representing three different types of sludges. Raw primary sludge was obtained from the Camden County Wastewater Treatment Plant. Anaerobically digested sludge (combined primary and secondary) was obtained from the Middletown Sewerage Authority and secondary biological sludge was obtained from the Evesham Township Wastewater Plant.

The shredded rubber tires of mixed sizes were obtained from the Emanuel Tire Company in Baltimore, Maryland. The shredded tires were relatively free of protruding steel belts because the belts had been removed by magnetic separation by the manufacturer. The mixed size shredded rubber tires were classified into three sizes: (1) 1.27-2.54 cm (1/2-1 in.), (2) 2.54-5.08 cm (1-2 in.), and (3) above 5.08 cm (2 in.). The tires were classified with a rotary trommel screen supplied by Royer Foundry and Machine Company, Kingston, Pennsylvania.

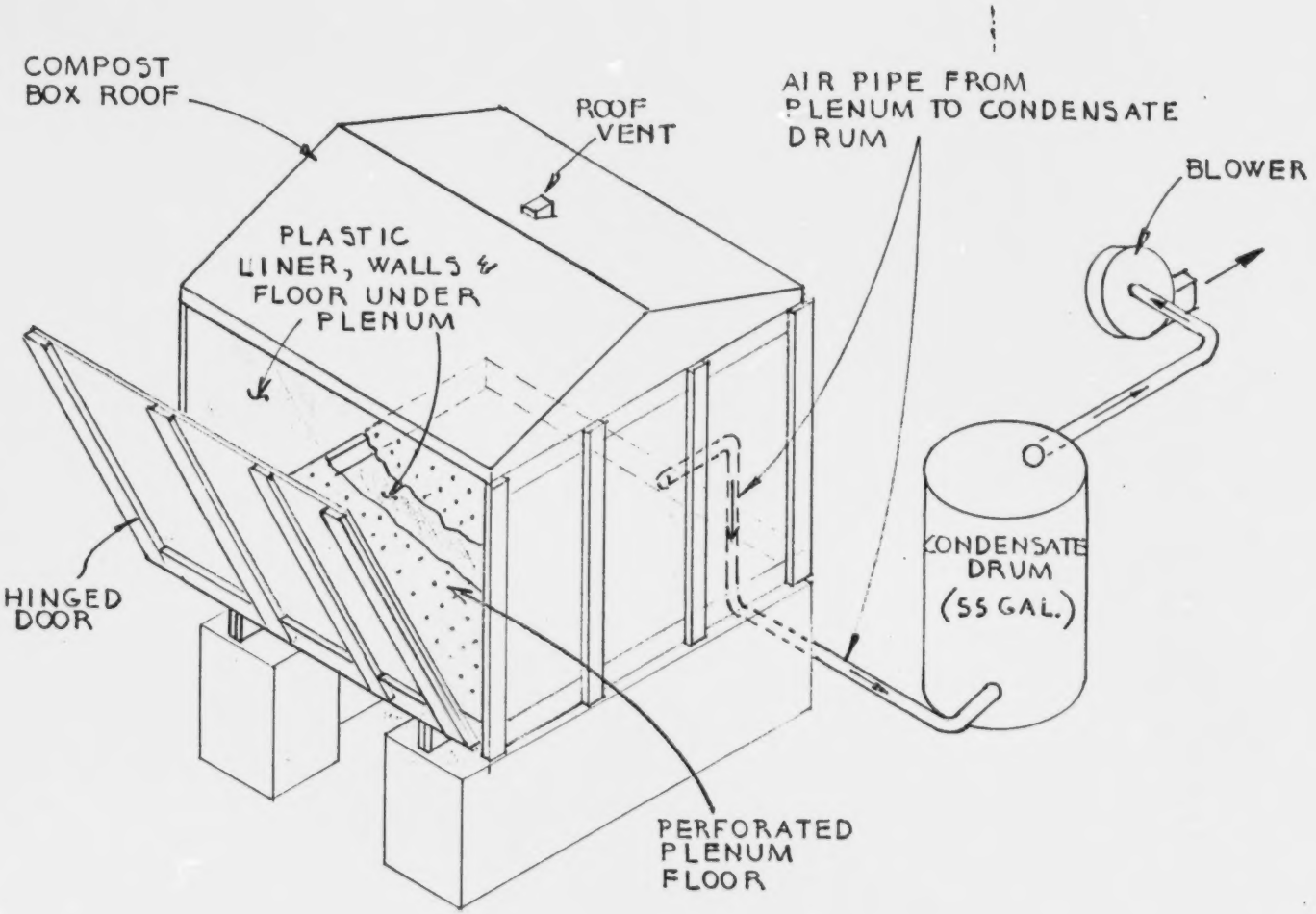

Figure 1 Schematic of compost vessel and aeration system.

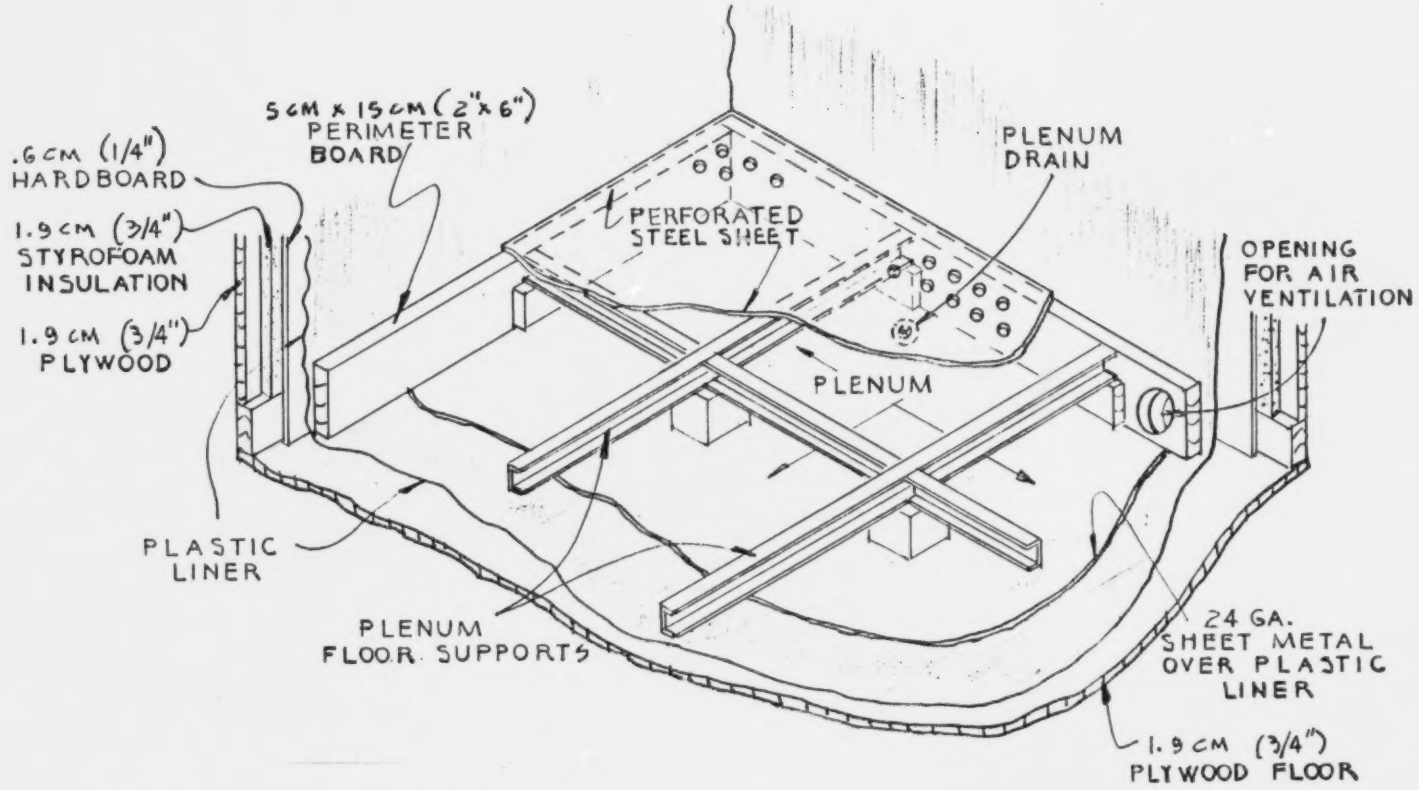

Figure 2 Partial cutaway view of plenum.

In addition to the shredded rubber, supplemental amendments, such as sawdust and recycled compost, were used for moisture and carbon control. The amendments were used to adjust the moisture content to the optimum range of between 50-60 percent. The sawdust also provided an additional carbon source.

To compare the performance of the various chip sizes, sludges and amendments, a number of parameters were evaluated:

1. Temperature. Temperatures were recorded at two depths within the composter for a period of approximately 15-20 days. Four thermocouples were placed at both the 0.3 and 0.6 meter levels (1 and 2 foot level). The four thermocouples in each layer were connected in parallel to produce an average temperature for the layer. (4) These readings were used to determine if sufficient temperatures were developed to destroy pathogens (3 days at 55°C). Since the composters were temperature controlled by a thermostat, the thermocouple readings were not used to compare compost performance but to ensure proper temperature elevation for pathogen control.

2. Airflow. Since the temperature within the composters was maintained at a constant setpoint (55°C), the airflow to each composter varied. The ability to reduce pile temperature was dependent on a number of variables including mass flow, heat transfer efficiency, humidity, ambient air temperature, and evaporation. A computer data collection system was used to record the aeration blower cycle time. This represented the time each fan was on during the experiment.

3. Moisture Content. The ability of the composting process to remove moisture was another indicator of performance. Therefore, each of the composting vessels was sampled prior to mixing and following screening to determine the initial and final moisture contents. Samples were collected from three different layers within the pile and composited. Three analyses were run for each composite using the procedure described in Standard Methods (5) for sludge.

4. Volatile Solids. The organic matter content of the composting sludge was estimated using the volatile solids content. As organic matter was destroyed by microbial activity, the volatile solids content of the composting sludge should have decreased. The reduction in volatile solids content was used as an indicator of composter performance. The analyses were run according to the procedure described in Standard Methods (5).

5. Carbon. The sewage sludge contained carbon as part of the organic matter fraction. Therefore, carbon was also lost due to organic matter destruction and was an indicator of compost performance. The carbon content in the sewage sludge was determined by the wet combustion method of Allison (6). The sludge samples were digested in a 60:40 mixture of sulfuric and phosphoric acid containing potassium dichromate. The mixture was boiled at 210°C which was sufficient to ensure complete oxidation of the carbonaceous matter. Carbon dioxide was evolved and was collected on an absorbent and weighed. The difference in weight between a blank and the sample was used to calculate the amount of carbon.

6 Nitrogen. The sewage sludge also contained nitrogen, which was an essential component for microbial growth. The proper C/N ratio was essential for efficient composting. Nitrogen was determined according to the methods described by Williams (7). It included the digestion of the sample in a mixture of K_2SO_4+$CuSO_4$ and concentracted H_2SO_4. The digested sample was transferred to a distillation apparatus where the nitrogen was collected in a boric acid solution. The concentration was determined using HCl titration.

7. Heavy Metals. The initial heavy metal content of the sludge and the final content in the compost were determined. This information was collected to determine the contribution, if any, of heavy metals to the compost from the shredded rubber tires. The heavy metals were analyzed using the procedures described in Standard Methods (5) and Methods of Soil Analysis (8). A sample of the sludge or compost was digested in a 1:4 mixture of perchloric acid ($HClO_4$) and concentrated nitric acid (HNO_3). The concentrations of the Fe, Cu, Zn, Pb, Cd and Ni were determined by Atomic Absorption Spectrometry (Perkin Elmer Model). All samples were analyzed in triplicate.

8. Porosity. Porosity tests were conducted on samples of rubber chip and sludge mixtures. The samples were obtained after mechanical mixing, just prior to entering the compost vessels. Two samples were collected for each of the three rubber chip sizes and mix ratios tested. The porosity tests were conducted at the compost site following the porosity test method (No. 2) described in Sludge Composting and Utilization: A Design and Operating Manual (9).

SECTION 4

RESULTS AND DISCUSSION

The experimental trials were grouped into several categories referred to as sets (Table 1). Within each set the three composting vesels were run simultaneously and received the same sludge. The size of the bulking agent was varied for the first five trials in Set 1 to determine the optimum size; all subsequent trials used this optimum size rubber chip. The last three trials in Set 1 were used to determine the proper rubber-chip-to-sludge mix ratio; all subsequent trials used this optimum mix ratio. Sets 2, 3, and 4 were used to determine the effects of amendments, and to evaluate composting of the three types of sludge.

EXPERIMENT SET 1, RAW PRIMARY SLUDGE

Determination of Rubber Chip Size

In order to determine the optimum particle size of the shredded rubber for composting, three trials using the small, medium, and large size rubber chips were conducted and statistically analyzed using a Latin square design. The Latin square statistical design was used to eliminate the variation caused by different batches of the same sludge. The results for moisture content, volatile solids content, and total carbon content (Table 2) were used for the analysis. Sample calculations for percent reduction are presented in the appendix. Both the final value (screened compost) and the percent reduction were analyzed. Initially, a linear model with 3 factors (size, trial, and compost vessel) was considered. The analysis of variance did not show any significant difference among the compost vessels; therefore, the factor for compost vessel was dropped from the analysis. Secondly, the analysis of variance was rerun using the two remaining factors--size and trial. This analysis did show differences between the three trials for moisture content and volatile solids content even though each trial had identical treatments. This was due to the variability of the moisture content, volatile solids content, total carbon content, total nitrogen content, and heavy metals concentration in the initial sludges used in each of the trials. In addition, other factors such as ambient air temperature, ambient humidity, rubber chip moisture content, and screening carryover may have contributed to the variability among trials. However, examination of the parameters within each trial showed that the small rubber chip yielded compost with the lowest moisture content, volatile solids content, and total carbon content; followed by the medium size chips and the large size chips (see Table 2). This trend allowed the trials to be grouped together to calculate treatment means. The treatment (chip size) means were then used for least significant difference comparisons which are presented in Table 3.

TABLE 1. SUMMARY OF TREATMENTS FOR COMPOSTING EXPERIMENTS

Set	Trial	Date	Chip Size in Composting Vessel*	Type of Sludge+	Amendment	Mix Ratio#
1	1	09/05/84-09/18/84	S, M, L	Primary	None	2:1:0
1	2	10/16/84-11/04/84	S, M, L	Primary	None	2:1:0
1	3	11/08/84-11/27/84	S, M, L	Primary	None	2:1:0
1	4	03/06/85-03/25/85	S, M, Mixed	Primary	None	2:1:0
1	5	03/26/85-04/16/85	S, M, Mixed	Primary	None	2:1:0
1	6	08/14/85-09/03/85	S, S, S	Primary	None	X, Y, Z
1	7	09/05/85-09/23/85	S, S, S	Primary	None	Z, X, Y
1	8	09/28/85-10/14/85	S, S, S	Primary	None	Y, Z, X
2	1	04/17/85-05/03/85	S, S, S	Primary	Sawdust	2:1:1
2	2	05/06/85-05/22/85	S, S, S	Primary	Recycled compost	2:1:1
3	1	05/23/85-06/10/85	S, S, S	Anaerobically digested	Sawdust	2:1:1
3	2	06/12/85-07/01/85	S, S, S	Anaerobically digested	Recycled compost	2:1:1
4	1	07/03/85-07/22/85	S, S, S	Secondary Biological	Sawdust	2:1:1.5
4	2	07/24/85-08/12/85	S, S, S	Secondary Biological	Recycled compost	2:1:1.5

* Note: 3 composting vessels were used for each trial
S = Small 1.27-2.54 cm (0.5-1 in.),
M = Medium 2.54-5.08 cm (1-2 in.),
L = Large >5.08 cm (>2 in.),
Mixed = 50% Small + 50% Medium

+ Sources of sludge: Camden (Primary), Middletown (Anaerobically digested), Evesham (Secondary Biological)

Rubber chip to sludge to amendment mix ratio, where X = 1:1:0, Y = 2:1:0, and Z = 3:1:0

TABLE 2. MEAN COMPOSITION OF RAW PRIMARY SLUDGE AND COMPOST SAMPLES FOR EXPERIMENT SET 1, TRIALS 1-5

Parameter	Trial	Raw* Sludge	Compost Chip Sizes#				Percent Reduction Chip Sizes#			
			S	M	L	Mixed	S	M	L	Mixed
Moisture Content (%)+	1	73.7	40.6	52.0	60.7	-	90	80	72	-
	2	74.8	36.0	39.8	51.4	-	91	88	80	-
	3	74.0	51.7	54.9	57.8	-	81	77	73	-
	4	73.7	45.0	50.8	-	49.8	85	81	-	81
	5	73.7	32.5	47.8	-	31.7	93	83	-	92
Volatile Solids Content (%)Ŧ	1	79.8	54.8	62.3	61.9	-	69	58	59	-
	2	81.2	61.2	64.5	66.1	-	63	58	54	-
	3	80.5	62.7	65.5	66.4	-	59	54	52	-
	4	79.0	58.2	60.0	-	60.7	63	60	-	59
	5	86.4	67.2	74.6	-	70.2	68	55	-	63
Total Carbon Content (%)Ŧ	1	35.9	29.9	30.8	32.3	-	63	54	52	-
	2	39.6	30.1	32.5	34.4	-	63	57	52	-
	3	38.9	30.2	30.6	33.3	-	60	56	50	-
	4	37.3	24.9	27.3	-	26.1	66	61	-	63
	5	44.6	30.2	32.9	-	28.0	72	61	-	71

* Measured before mixing

S = Small 1.27-2.54 cm (0.5-1 in.), M = Medium 2.54-5.08 cm (1-2 in.), L = Large 5.08 cm (2 in.), Mixed = 50% Small + 50% Medium

+ Percent wet mass basis

Ŧ Percent dry mass basis

TABLE 3. RESULTS OF LEAST SIGNIFICANCE DIFFERENCE (LSD) TEST

FOR EXPERIMENT SET 1, TRIALS 1-3

Parameter	Grouping#	Mean	Chip Size
Moisture Content % Reduction	A A B	87.3 81.7 75.0	Small Medium Large
Volatile Solids Content % Reduction	A B B	63.7 56.7 55.0	Small Medium Large
Carbon Content % Reduction	A B C	62.0 55.7 51.3	Small Medium Large

Means with the same letter are not significantly different (alpha = 0.05, with 4 degrees of freedom)

When the first three trials were analyzed, no significant differences were found between the small and medium size rubber chips when the percent reduction in moisture content was examined. There was a significant difference between the small and large size. The least significant difference (LSD) test results for the percent reduction in volatile solids revealed no significant difference between the medium and large size. The small size was significantly different from the other two. The percent reduction in carbon content indicated that the three sizes were significantly different. The results of the statistical analysis show that the small and large size rubber chips were significantly different.

The statistical analysis confirmed the observed poor performance of the large rubber chip as a bulking agent; therefore, no further experiments using the large size chips were conducted.

Two additional experiments, Trials 4 and 5, were performed to determine if there was a significant difference between the small and medium size chips. In addition, a 1:1 mixture of the two sizes (i.e., mixed size) was tested in Trials 4 and 5.

The results for Trials 4 and 5 of this experimental set are presented in Table 2. Analysis of variance was run using 5 trials and 2 treatments (chip size). The small and medium size chips were compared using analysis of variance on the moisture content, volatile solids content, and total carbon content data. This revealed a significant difference at the 5 percent level between the small and medium size rubber chips for each parameter. These results indicated that the small size chip produced a better compost than the medium size chip. Hence, the medium size chip was eliminated from further use.

With only two trials using the mixed size chips, statistical comparisons were not made. However, the small size rubber chip outperformed the mixed size chip on the basis of percent reduction in moisture content, volatile solids content, and total carbon content. Based on these results, the small size chip was determined to be optimum.

Determination of Rubber-Chip-to-Sludge Mix Ratio

Three experiments (Trials 6, 7, and 8) were conducted to determine the proper rubber chip to sludge mix ratio. The shredded rubber to raw sludge mix ratios were 1:1, 2:1, and 3:1 by volume (see Table 1). These ratios were chosen based on experience with the static pile composting method used in the United States. The performance of each mix ratio was statistically evaluated using the moisture content, volatile solids content, and total carbon content data presented in Table 4. In addition, qualitative evaluations were made from observations during loading, composting, and screening.

Analysis of variance was run for trial and ratio using a Latin square design. The percent reduction values were the dependent variables. The analysis of variance showed no significant difference among the trials (see Table 5). A significant difference (5% level) was detected among the ratios for the volatile solids data. Therefore, an LSD test of the ratio means was performed. The LSD test showed that the 3:1 and 2:1 mix ratios were not significantly different from each other, but were significantly different from the 1:1 mix ratio (see Table 5). The higher means for the 3:1 and 2:1 mix ratio indicate greater volatile solids reduction, hence better composting.

The analysis of variance using moisture content and carbon content data were significant at the 6 and 8 percent levels for variation among the mix ratios. Although not significant at the 5 percent level, the LSD test was run for these two data sets for qualitative comparisons. The 2:1 mix ratio composted better than the 1:1 mixture as indicated by the greater reduction in moisture content and carbon content.

During loading, the 1:1 mix ratio was observed to be the stickiest and to form the most sludge balls due to the high sludge content. The 2:1 and 3:1 mix ratios mixed more uniformly, forming fewer sludge balls with the inclusion of the additional rubber chips. A porosity test for Trial 6 (two replicates for each treatment) showed that the porosity increased as the amount of rubber chips in the mix increased. The measured porosities were 42.9, 45.4, and 52.1 percent for rubber chip to sludge mix ratios of 1:1, 2:1, and 3:1, respectively. Composting odors were most noticeable from the 1:1 mix ratio treatment and least noticeable from the 3:1 treatment. Odors were detected strictly on a qualitative basis. Screening carryover was greatest for the 1:1 mix and pockets of wet, partially composted sludge were also observed during unloading.

The statistical analysis, confirmed by field observations, identified the 1:1 mix ratio as being unsatisfactory. No statistically significant differences were found between the 2:1 and 3:1 mix ratios. These two mix ratios were judged to be very similar in terms of ease of handling and composting performance. Even though these two mix ratios were very similar, the 2:1 mix ratio was considered optimum because fewer rubber chips were required for the compost mixture. This maximized sludge utilization and minimized the quantity of bulking agent handled. This was important in light of the conclusion that an amendment such as sawdust must be added to the sludge when rubber chips are used for bulking (see "Composting Performance" and Experiment Set 2 discussions following).

TABLE 4. MEAN COMPOSITION OF RAW PRIMARY SLUDGE AND COMPOST SAMPLES FOR EXPERIMENT SET 1, TRIALS 6-8

Parameter	Trial	Raw* Sludge	Compost Mix Ratio# 1:1	Compost Mix Ratio# 2:1	Compost Mix Ratio# 3:1	Percent Reduction Mix Ratio# 1:1	Percent Reduction Mix Ratio# 2:1	Percent Reduction Mix Ratio# 3:1
Moisture Content, (%)+	6	71.5	54.8	32.6	43.5	63	89	83
	7	70.2	45.8	35.4	37.0	75	87	87
	8	72.5	48.7	45.6	42.0	75	79	83
Volatile Solids Content, (%)‡	6	70.4	61.5	46.2	47.6	33	64	62
	7	74.8	63.2	56.1	52.4	42	57	63
	8	71.8	58.2	55.9	53.1	45	50	56
Total Carbon Content, (%)‡	6	26.1	20.2	15.3	17.4	41	68	62
	7	29.0	19.4	19.0	20.1	54	62	63
	8	27.3	18.4	17.7	16.8	54	60	63

* Measured before mixing

S = Small size (1.27-2.54 cm) rubber chip:raw sludge, by volume

+ Wet mass basis

‡ Dry mass basis

TABLE 5. SUMMARY OF LEAST SIGNIFICANT DIFFERENCE (LSD) TEST FOR EXPERIMENT SET 1, TRIALS 6 - 8

	Significance Level (P value)				
	Source of Variation		Least Significant Difference (LSD) Test*		
Parameter	Trial	Ratio	Grouping#	Mean	Ratio
Moisture Content % Reduction	0.585	0.062+	A	85.0	2:1
			A	84.3	3:1
			B	71.0	1:1
Volatile Solids Content % Reduction	0.800	0.042	A	60.3	3:1
			A	57.0	2:1
			B	40.0	1:1
Carbon Content % Reduction	0.850	0.077+	A	63.3	2:1
			A B	62.7	3:1
			B	49.7	1:1

* The significance level of statistical test, alpha = 0.05, with 4 degrees of freedom

+ Not significant at the 5% level. LSD shown for qualitative comparisons only

Means with the same letter are not significantly different

Total Nitrogen Content

Table 6 gives the total nitrogen content and the carbon to nitrogen (C/N) ratio for the first five trials of Set 1 using raw primary sludge from Camden, New Jersey. The C/N ratio of the raw sludge ranged from approximately 11 to 19, which was lower than the optimum range of 25 to 30. Nitrogen content and C/N ratio for Trials 6, 7, and 8 of Set 1 are given in Table 7. This sludge had a higher total nitrogen content than the sludge obtained 5 to 12 months earlier. The higher total nitrogen content coupled with lower total carbon content resulted in C/N ratios less than 10.

Heavy Metals

The results of the heavy metal analysis for Experiment Set 1 are presented in Tables 8, 9, and 10. These tables show that heavy metal levels increased due to the concentrating effect as organic matter was decomposed. Occasionally, the concentration of a heavy metal did not change, or decreased after the composting cycle (i.e., cadmium for Trial 1, small size chip and lead for Trial 5, all treatments). This was due to screening carryover and the heterogeneous nature of the screened compost samples.

The concentrations of zinc (Zn) and iron (Fe) increased as a result of using shredded rubber tires (Table 8). Zinc oxide, used in the manufacturing of tires, was the source of zinc in the compost. The increase in iron was due to steel belts and rim beads found in rubber chips that had eluded magnetic separation. Although steel was infrequently observed, it caused no handling problems and appeared to be randomly distributed among the rubber chip sizes. The release of these two heavy metals during the composting process was also reported by Higgins, et al. (2) and Higgins (10).

TABLE 6. NITROGEN ANAYLSIS FOR EXPERIEMENT SET 1, TRIALS 1-5

Parameter	Trial	Raw* Sludge	Compost Chip Sizes # S	M	L	Mixed
Total Nitrogen Content (%)+	1	2.8	1.8	2.1	2.1	-
	2	2.6	1.5	2.0	2.1	-
	3	2.2	1.8	2.1	2.3	-
	4	3.3	2.4	2.5	-	2.3
	5	2.3	2.1	2.2	-	2.1
Carbon to Nitrogen Ratio (C/N)	1	12.6	16.6	14.7	15.4	-
	2	15.0	20.1	16.2	16.4	-
	3	17.6	16.8	14.6	14.5	-
	4	11.4	10.4	10.9	-	11.3
	5	19.4	14.4	15.0	-	13.3

* Measured before mixing

S = Small (1.27-2.54 cm), M = Medium (2.54-5.08 cm), L = Large (> 5.08 cm), and Mixed = 50% Small + 50% Medium

+ Dry mass basis

TABLE 7. NITROGEN ANAYLSIS FOR EXPERIMENT SET 1, TRIALS 6-8

Parameter	Trial	Raw* Sludge	Compost Mix Ratio# 1:1	2:1	3:1
Total Nitrogen Content (%)+	6	2.9	2.3	2.4	2.1
	7	3.4	2.7	2.6	2.7
	8	3.8	3.0	3.0	2.7
Carbon to Nitrogen Ratio (C/N)	6	9.0	8.8	6.4	8.3
	7	8.5	7.2	7.3	7.4
	8	7.2	6.1	5.9	6.2

* Measured before mixing

Small size (1.27-2.54 cm) rubber chip:raw sludge, by volume

+ Dry mass basis

TABLE 8. HEAVY METAL COMPOSITION OF RAW PRIMARY SLUDGE AND COMPOST SAMPLES FOR FIVE CYCLES, EXPERIMENT SET 1, TRIALS 1-5

Heavy Metal	Trial	Raw Sludge* (mg/kg)	Compost (mg/kg)* Chip Sizes# Small	Medium	Large	Mixed
Cd	1	46.7	46.7	47.5	48.3	-
	2	30.0	40.0	40.0	38.3	-
	3	30.0	38.3	36.7	38.3	-
	4	55.0+	55.0	60.8	-	61.7
	5	42.5	43.3	45.0	-	51.7
Pb	1	176.7	242.5	252.5	248.3	-
	2	160.0	220.8	228.3	207.5	-
	3	131.7	150.8	156.7	181.7	-
	4	165.8	190.8	157.5	-	150.8
	5	225.8	179.2	120.0	-	117.5
Ni	1	78.3	95.0	93.8	107.5	-
	2	57.5	81.8	145.8	100.0	-
	3	40.0	63.3	60.0	66.7	-
	4	73.3	86.7	89.2	-	101.7
	5	58.8+	65.0+	55.0	-	55.0
Cu	1	900.8	942.5	1,007.5	1,049.2	-
	2	839.2	1,108.3	1,209.2	1,100.8	-
	3	607.5	815.0	790.8	851.7	-
	4	856.7	835.0	995.8	-	880.0
	5	500.0	633.3	616.7	-	625.0
Zn	1	1,213	2,408	1,918	1,902	-
	2	1,119	2,858	2,128	1,871	-
	3	895	2,182	1,756	1,586	-
	4	1,214	2,208	1,569	-	1,852+
	5	1,033	1,475+	1,433	-	1,625+
Fe	1	11,833	10,267	19,192	25,817	-
	2	6,890	20,012	26,617	22,222	-
	3	7,738	15,458	19,531	18,118	-
	4	9,375	22,675	17,688+	-	19,288+
	5	9,183	13,375+	11,308	-	13,375+

* Mean of 3 replicates; analyses done before mixing

Small (1.27-2.54 cm), Medium (2.54-5.08 cm), Large (>5.08 cm), and Mixed = 50% Small + 50% Medium

+ Mean of 2 replicates

TABLE 9. HEAVY METAL COMPOSITION OF RAW PRIMARY SLUDGE AND COMPOST SAMPLES FOR EXPERIMENT SET 1, TRIALS 6-8

Heavy Metal	Trial	Raw Sludge* (mg/kg)	Compost (mg/kg)* Mix Ratio # 1:1	2:1	3:1
Cd	6	32.5	32.5	26.7	25.0
	7	37.5	40.0	35.0	35.0
	8	41.7	44.0	41.3	38.3
Pb	6	169.2	163.3	169.2	205.8
	7	164.2	176.7	261.7	202.5
	8	138.0	166.0	171.0	167.3
Ni	6	64.2	55.0	53.3	55.0
	7	52.5	57.5	56.0	57.5
	8	64.3	76.0	88.7	71.0
Cu	6	790.0	882.5	677.5	628.3
	7	690.8	817.5	762.5	837.5
	8	886.3	1,030.7	993.7	904.3
Zn	6	955	1,819	1,498	1,751
	7	918	1,476	1,625	1,742
	8	959	1,639	1,669	1,837
Fe	6	12,700	18,942	23,400	26,050
	7	12,550	19,492	24,767	27,158
	8	14,021	21,065	24,643	23,431

* Mean of 3 replicates; analyses done before mixing

Small size (1.27-2.54 cm) rubber chip to sludge, by volume

TABLE 10. SUMMARY OF HEAVY METAL LEVELS FOR FIVE CYCLES, EXPERIMENT SET 1, TRIALS 1-5

Heavy Metal	Trial	Raw Sludge (mg/kg)		Compost (mg/kg)		Percent Change (%)
		Mean*	Standard Deviation	Mean*	Standard Deviation	
Cd	1	46.7	1.4	46.7	2.9	0
	2	30.0	0	40.0	0	33
	3	30.0	0	38.3	1.4	28
	4	55.0+	3.5	55.0	6.6	0
	5	42.5	2.5	43.3	2.9	2
Pb	1	176.7	15.1	242.5	21.8	37
	2	160.[illegible]	11.5	220.8	10.1	38
	3	131.7	11.8	150.8	7.6	14
	4	165.8	26.0	190.8	15.1	15
	5	225.8	50.6	179.2	36.4	-21
Ni	1	78.3	1.4	95.0	0	21
	2	57.5	0	81.8	2.9	42
	3	40.0	0	63.3	5.2	58
	4	73.3	12.3	86.7	11.5	18
	5	58.8+	23.0	65.0+	7.1	10

* Mean of 3 replicates; analyses done before mixing

+ Mean of 2 replicates

(continued)

TABLE 10 (continued)

Heavy Metal	Trial	Raw Sludge (mg/kg) Mean*	Raw Sludge (mg/kg) Standard Deviation	Compost (mg/kg) Mean*	Compost (mg/kg) Standard Deviation	Percent Change (%)
Cu	1	900.8	36.1	942.5	0	5
	2	839.2	2.9	1,108.3	24.5	32
	3	607.5	58.6	815.0	13.0	34
	4	856.7	220.0	835.0	116.8	-2
	5	500.0	139.2	633.3	137.7	27
Zn	1	1,213	22	2,408	31	98
	2	1,119	14	2,858	94	156
	3	895	13	2,182	56	144
	4	1,214	190	2,208	214	82
	5	1,033	471	1,475	71	43
Fe	1	11,833	22	19,267	462	63
	2	6,890	0	20,012	549	190
	3	7,738	276	15,458	98	100
	4	9,375	1,250	22,675	1,381	142
	5	9,183	4,336	13,375+	318	46

* Mean of 3 replicates; analyses done before mixing

+ Mean of 2 replicates

Examination of Table 8 revealed a pattern between the chip size and the concentration of Zn. In the first four of the five trials, the highest levels of Zn were found in the compost produced using the small size rubber chip. The lowest Zn levels were found when the large size chips were used. This finding was attributed to the abrasion of the rubber chips during loading, unloading, and screening resulting in small but undetectable particles being incorporated into the sludge or compost matrix. The small size rubber chips had the greatest surface area per unit volume. Conversely, the largest chip size had the lowest surface area per unit volume. Therefore, the small chips would contribute more abraded particles to the compost samples. This is also illustrated in Figure 3 where the small size chips produced a greater percent increase in Zn concentration than the medium size for Trials 1 through 5. No correlation was found between chip size and heavy metal concentration for cadmium, lead, nickel, or copper.

Trials 1 through 5 showed that the rubber chips contributed Zn and Fe to the compost. Therefore, it was expected that the greater the percentage of rubber chips in the mix, the higher the concentration of these two metals in the compost. The heavy metal concentrations for Trials 6, 7, and 8 presented in Table 9 and Figures 4 and 5 showed this trend for two of the three trials. Generally, the 1:1 mixture had the lowest level of Zn and Fe and the 3:1 mixture the highest. The concentration of Fe (in the compost) was lowest for the 1:1 mix ratio for all three trials.

The percent change in concentration of cadmium, lead, nickel, and copper for trials 1-5 are shown in Table 10 and Figure 6. The results indicate that increases in the level of these heavy metals were due to the concentrating effect of composting as organic matter was destroyed and that fluctuations in the percent change were due to sludge and sampling errors and were not a result of any observable pattern.

The percent change in zinc and iron for trials 1-5 are shown in Table 10 and Figures 3 and 7. The results indicate that substantial increases in Zn and Fe occurred. An observable pattern, as shown in Figures 3 and 7, was evident; the percentage increase reached a maximum after two cycles of use before beginning a gradual decline. This trend is expected to continue as the rubber chips are continually recycled.

Composting Temperatures

Temperature readings for the middle of the compost pile (0.6 meter level) were averaged for each day and plotted in Figures 8, 9, 10, 11, 12, 13, 14, and 15. The figures show that the set point composting temperature (55°C) could be maintained for most trials, but for a few trials an average daily temperature of 55°C was not reached. These figures do not show a pattern between the mass temperature and the bulking agent size or the mix ratio. Note that Trial 1 did not have thermostat regulated temperature, rather only time clock controlled ventilation. The thermostat for the 1:1 mix ratio treatment of Trial 6 malfunctioned, leaving that compost vessel with time clock controlled ventilation. A new thermostat was installed prior to the next experiment.

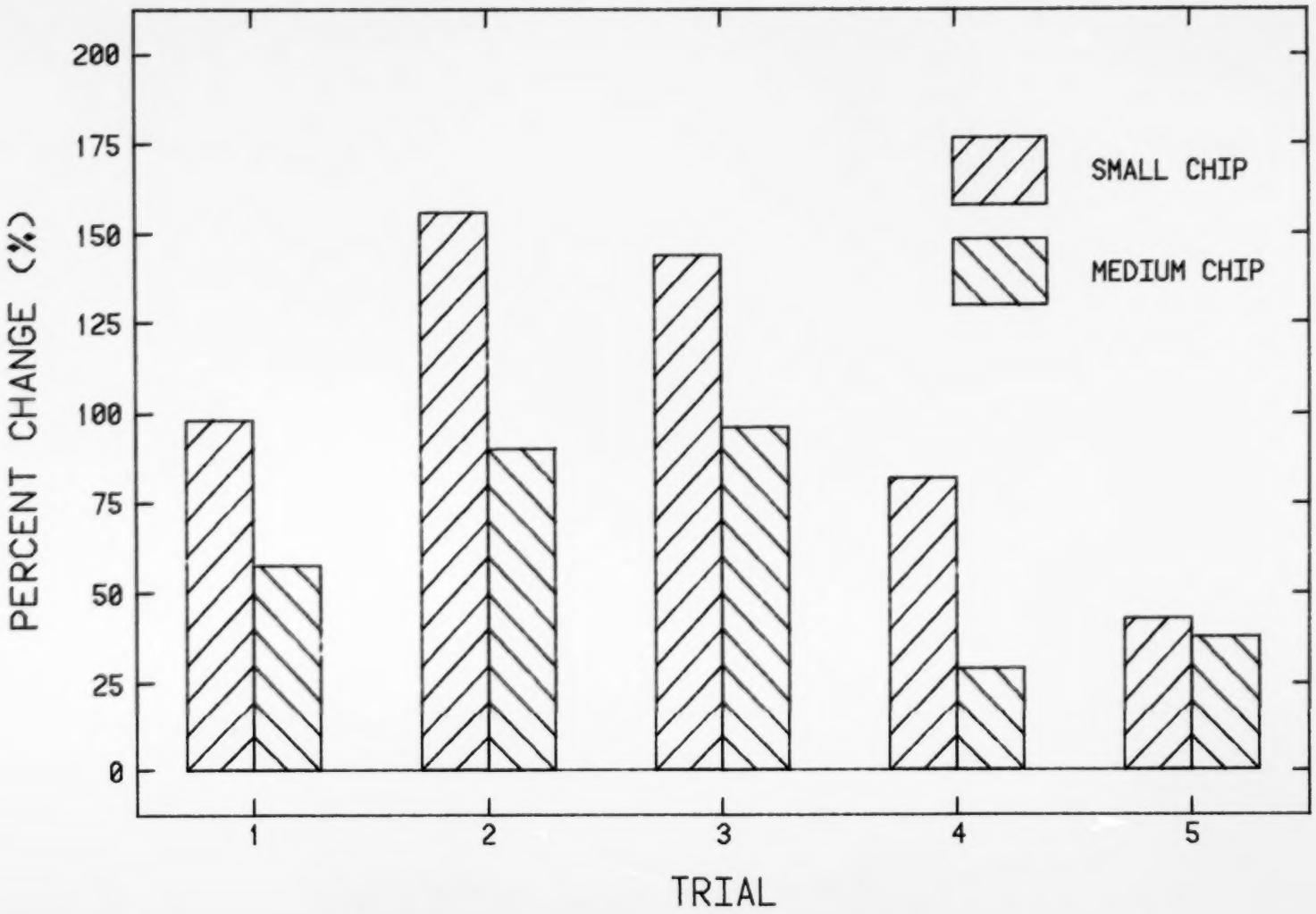

Figure 3 Change in zinc concentration after five cycles, Experiment Set 1, Trials 1-5.

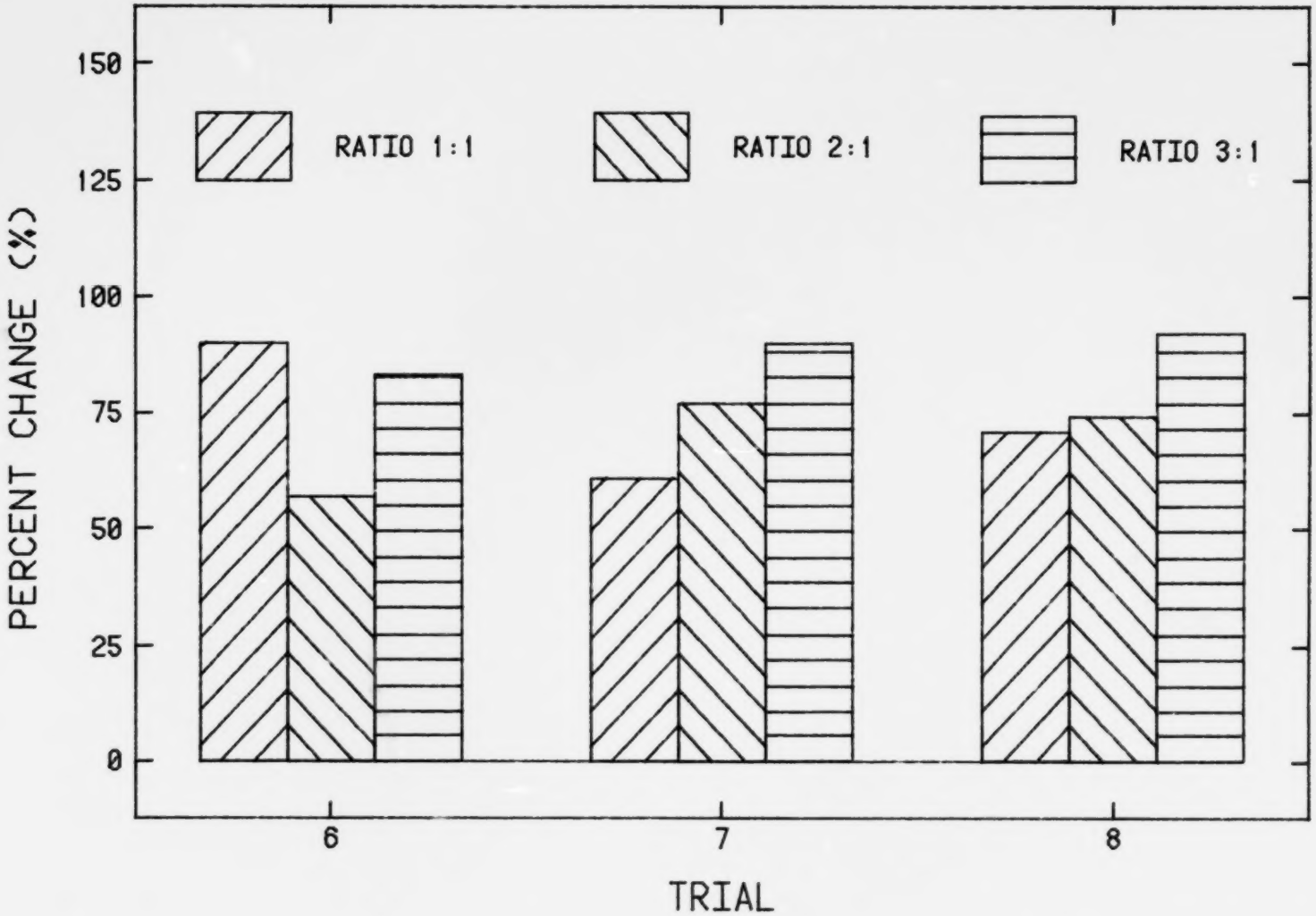

Figure 4 Effect of mix ratio on the change in zinc concentration, Experiment Set 1, Trials 6-8.

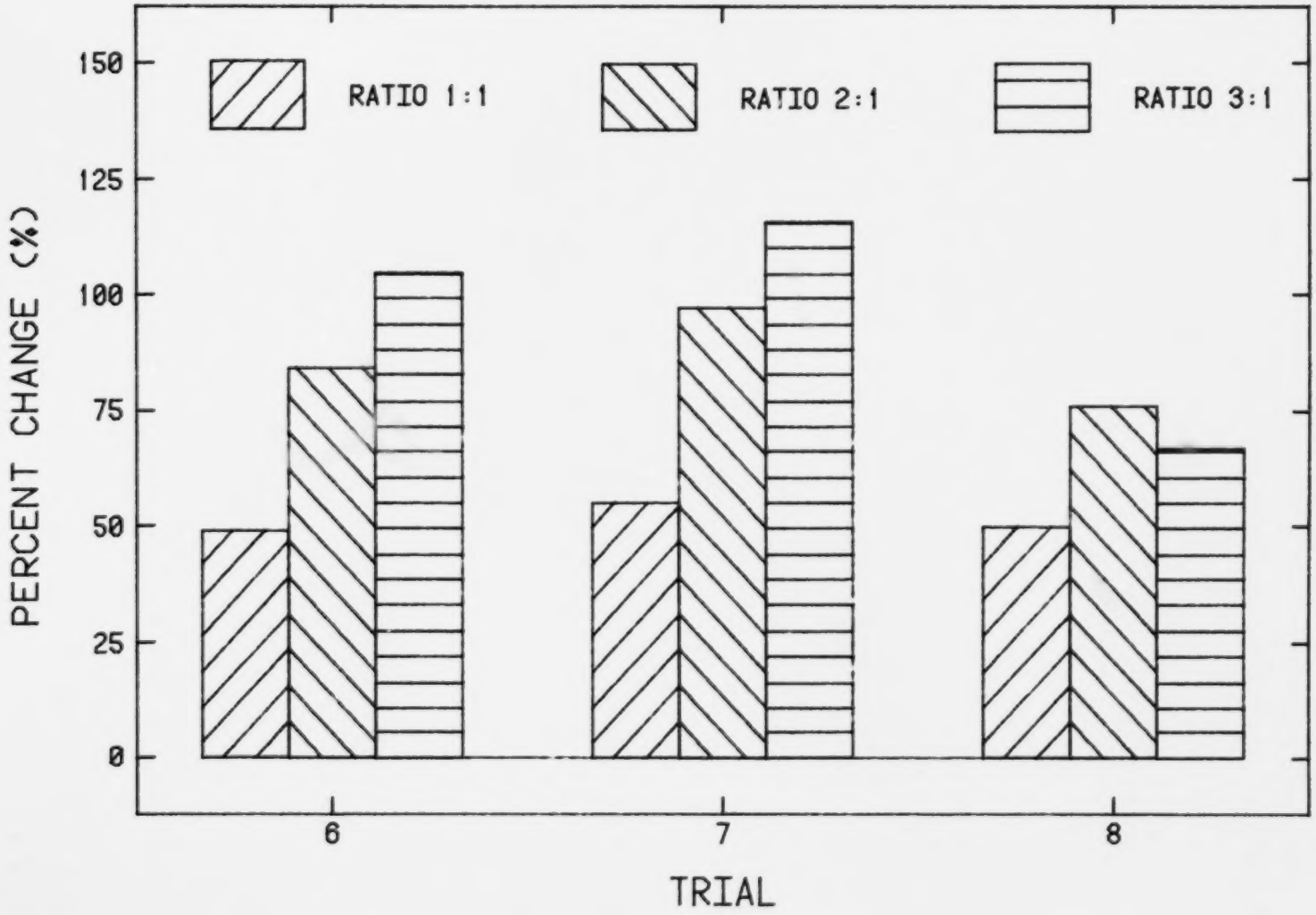

Figure 5 Effect of mix ratio on the change in iron concentration, Experiment Set 1, Trials 6-8.

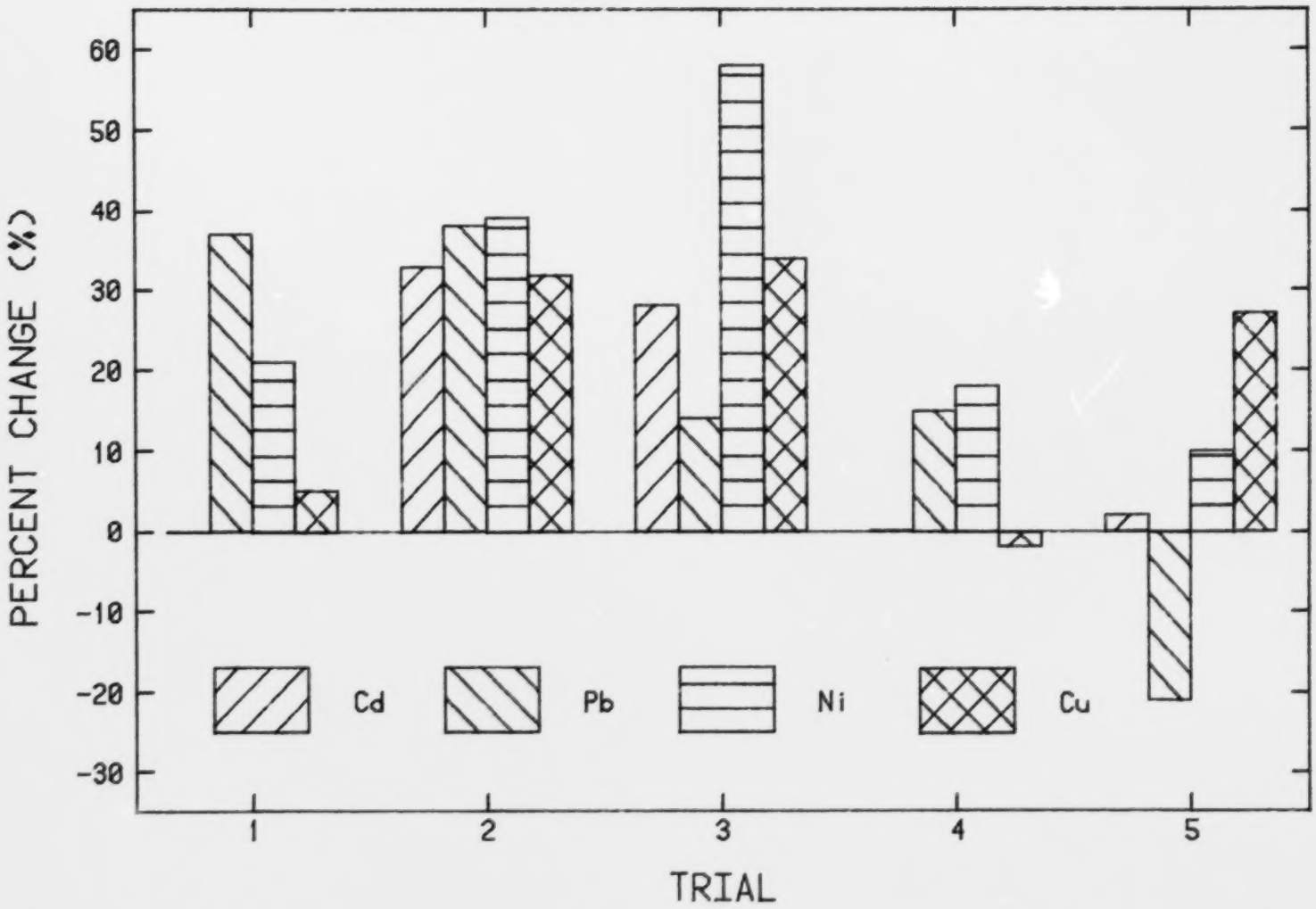

Figure 6 Change in heavy metals concentration after five cycles, Experiment Set 1, Trials 1-5.

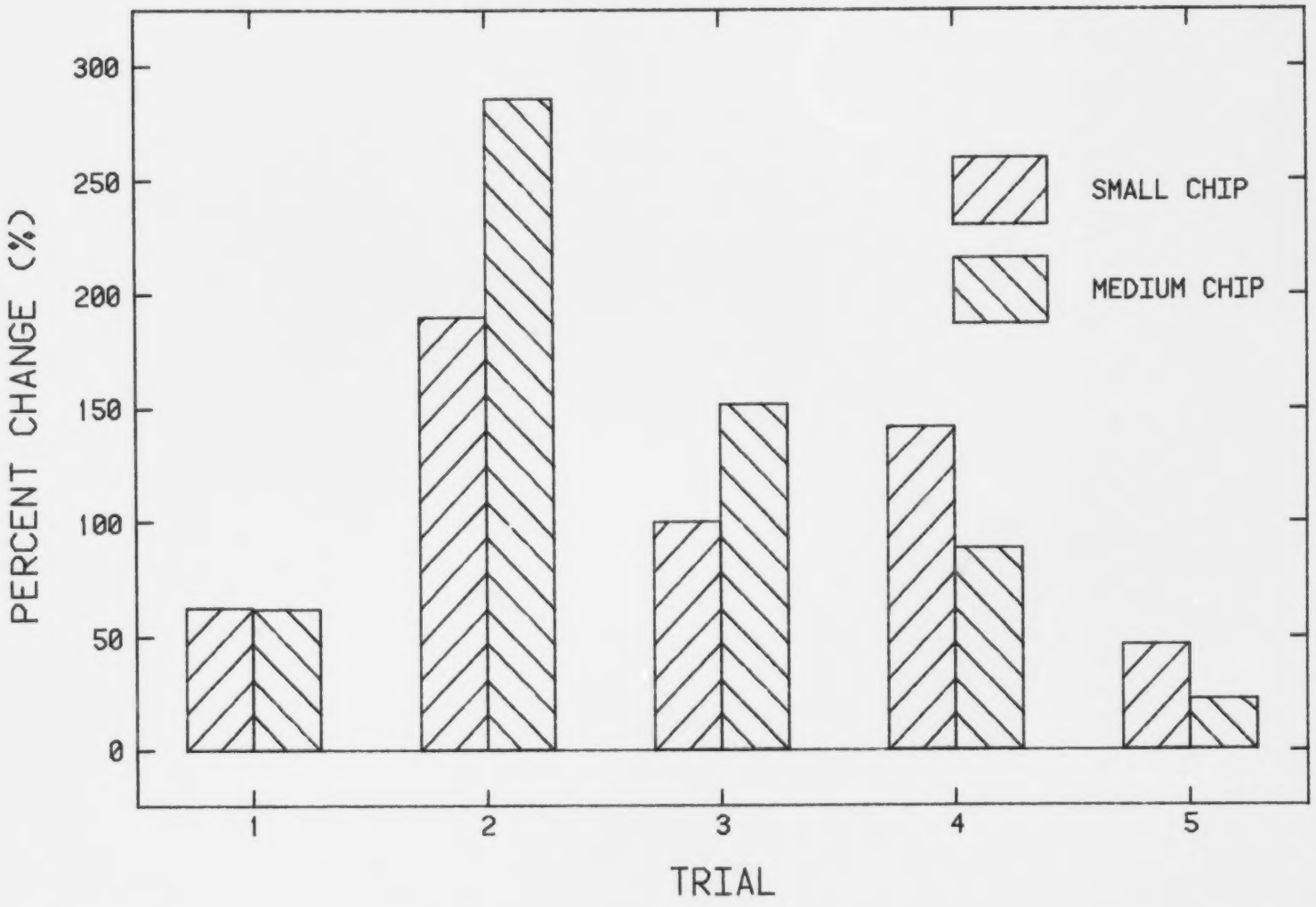

Figure 7 Change in iron concentration after five cycles, Experiment Set 1, Trials 1-5.

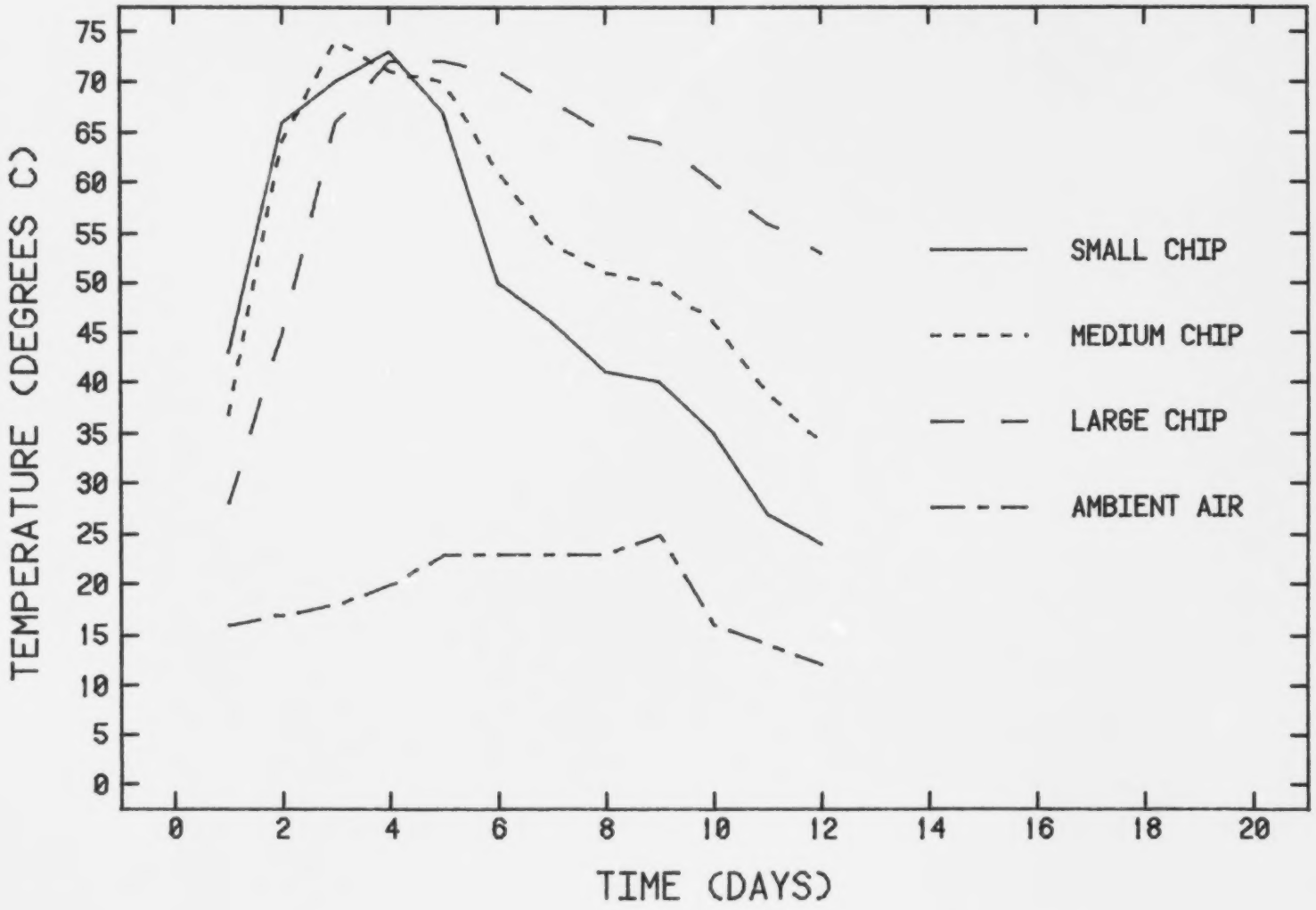

Figure 8. Ambient air and average daily temperatures, Experiment Set 1, Trial 1.

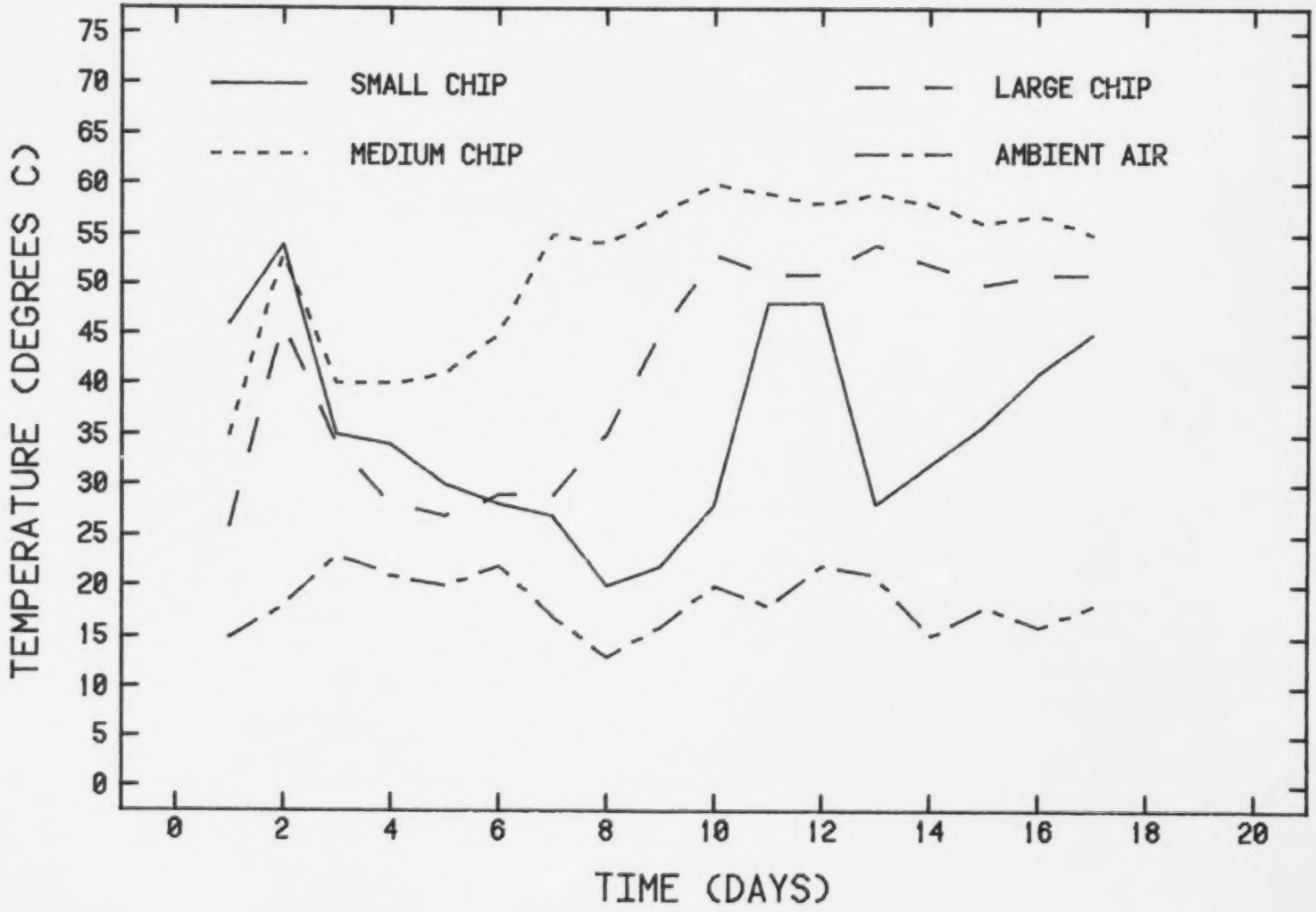

Figure 9. Ambient air and average daily temperatures, Experiment Set 1, Trial 2.

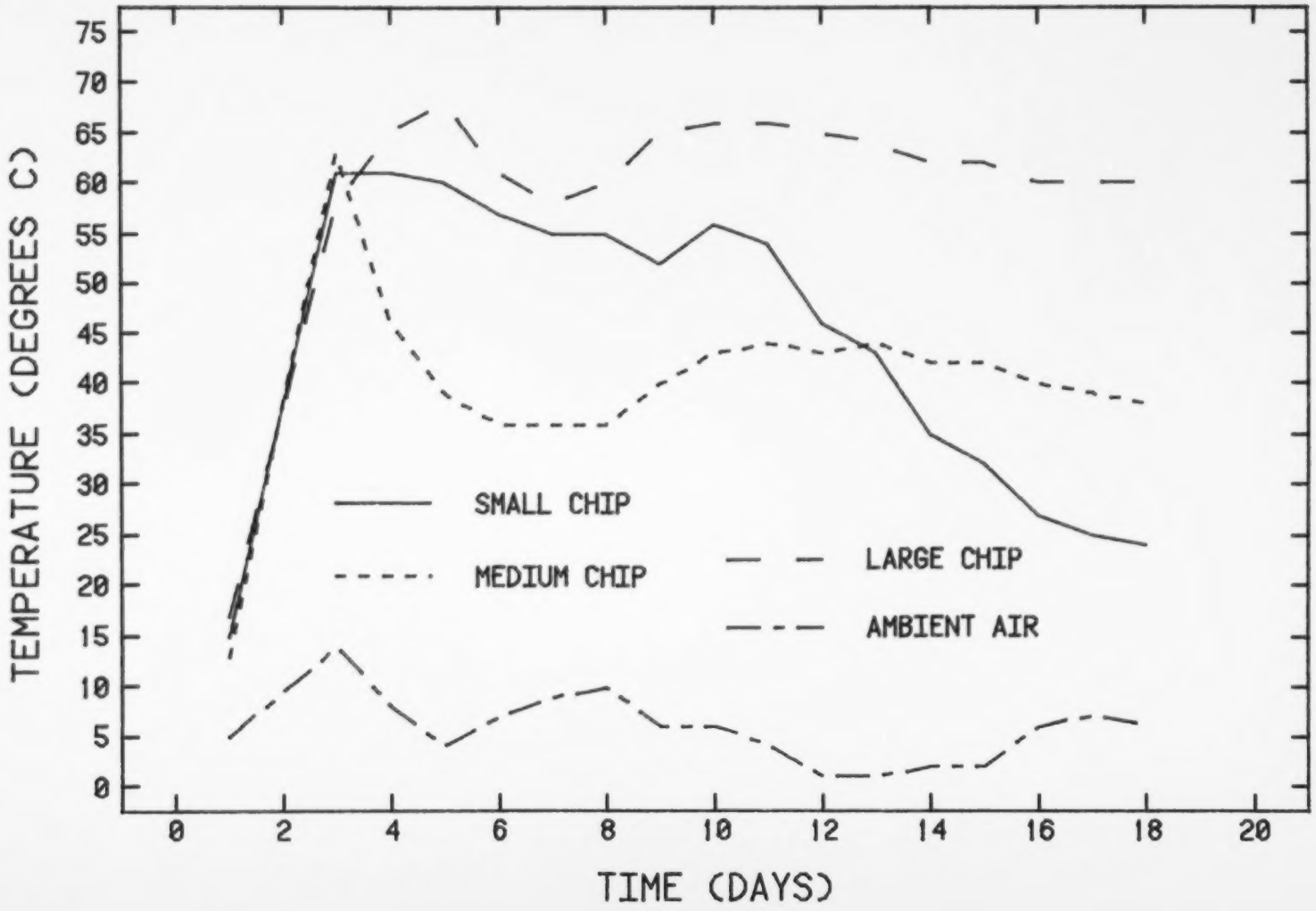

Figure 10. Ambient air and average daily temperatures, Experiment Set 1, Trial 3.

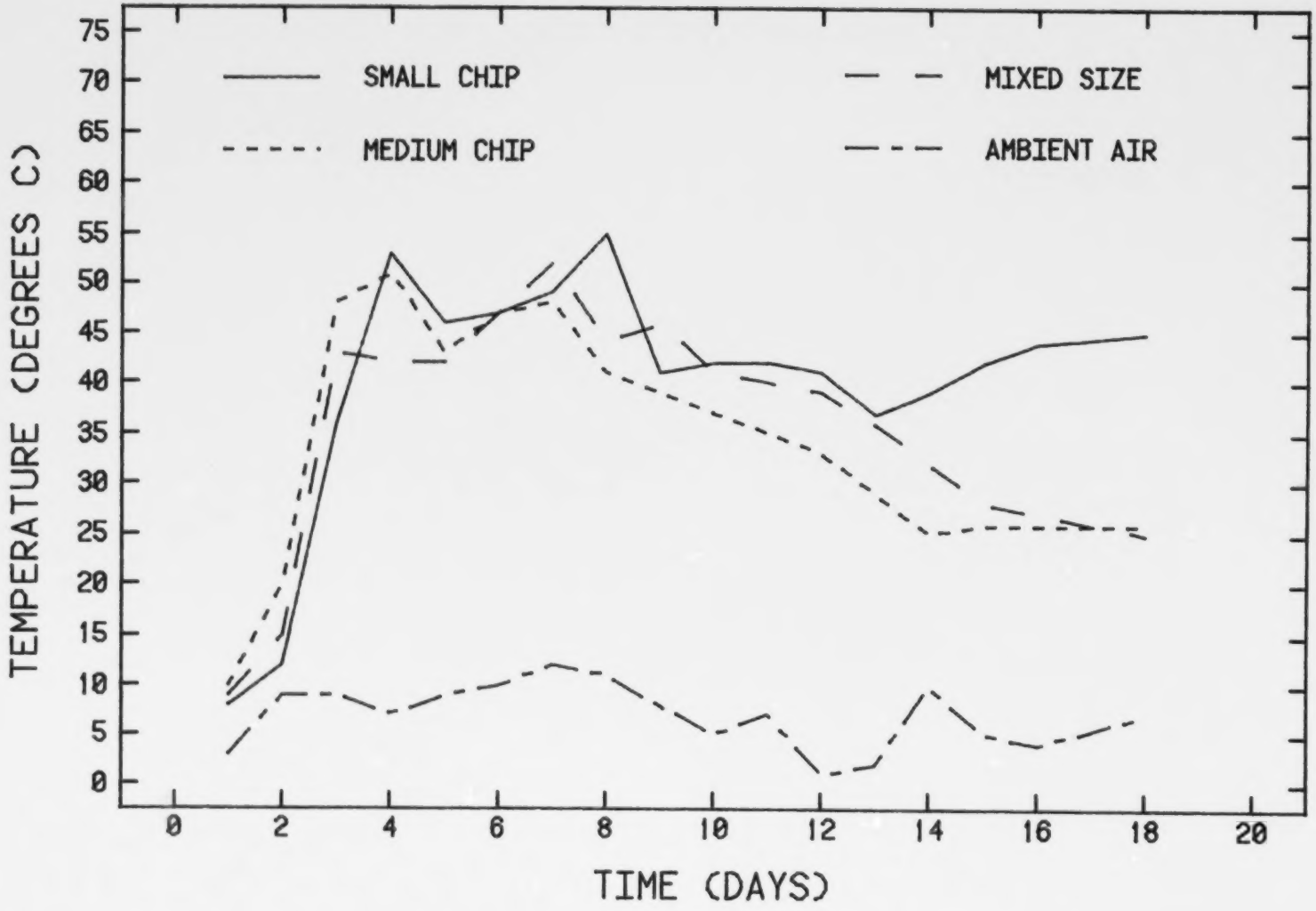

Figure 11. Ambient air and average daily temperatures, Experiment Set 1, Trial 4.

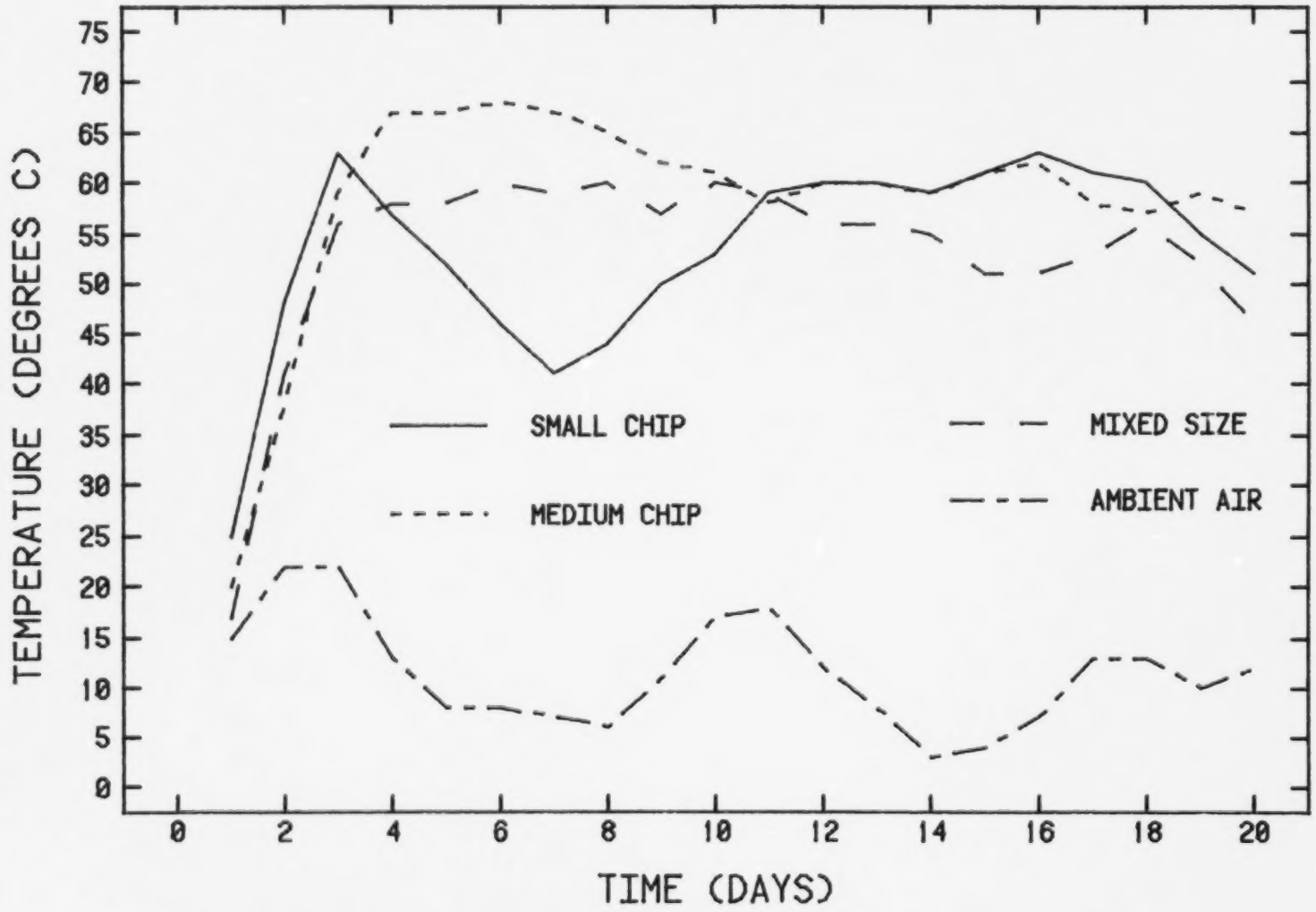

Figure 12. Ambient air and average daily temperatures, Experiment Set 1, Trial 5.

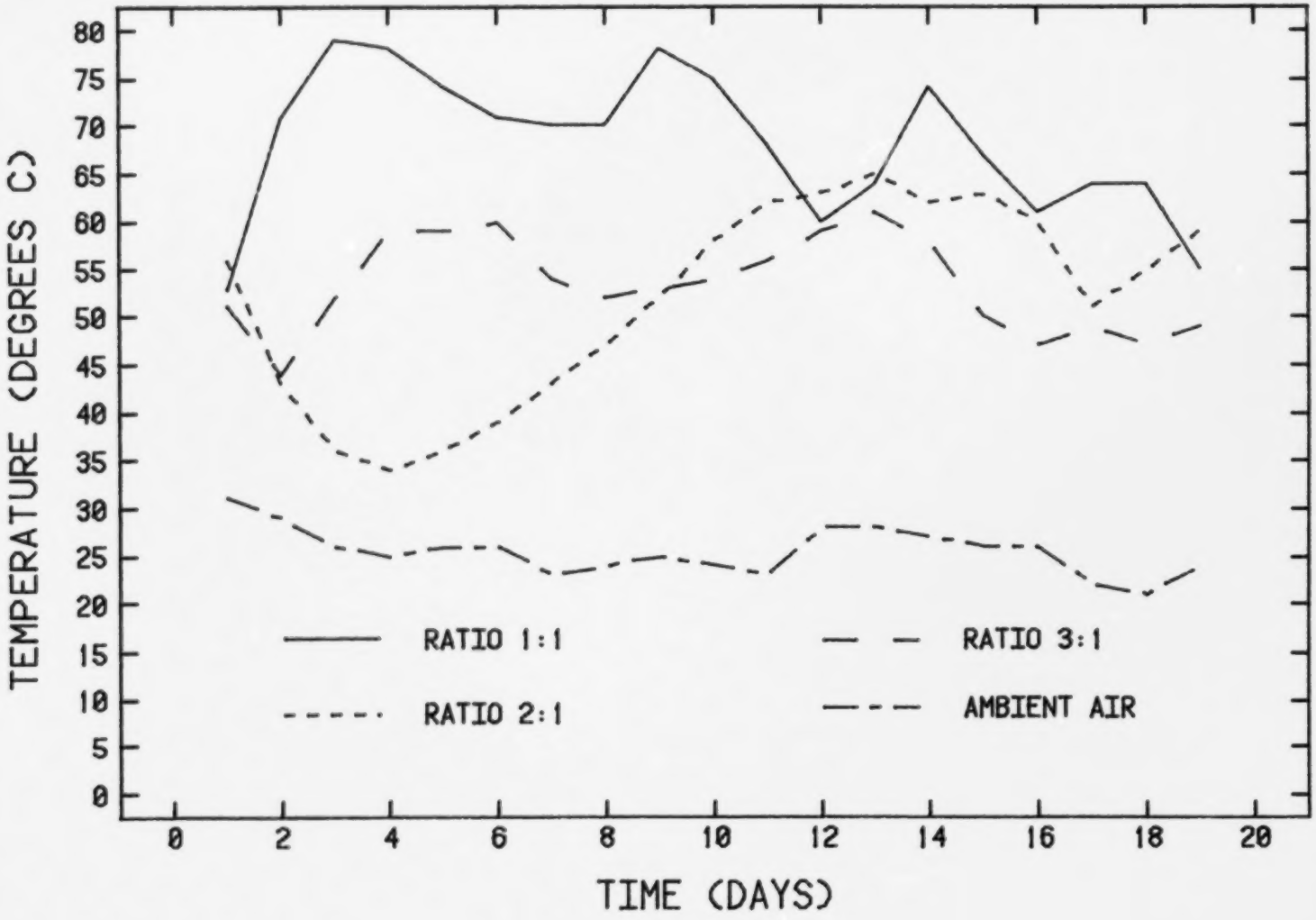

Figure 13. Ambient air and average daily temperatures, Experiment Set 1, Trial 6.

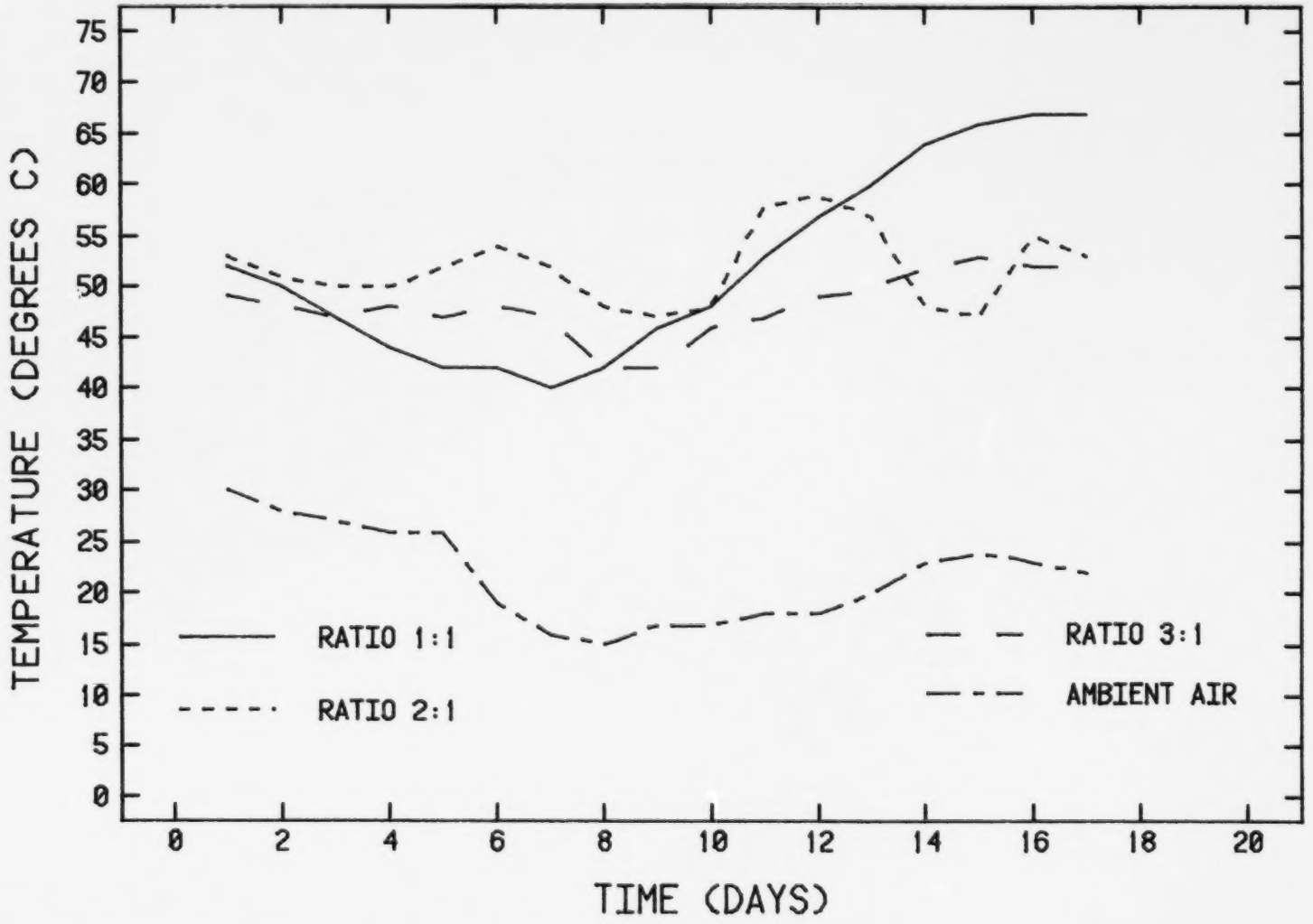

Figure 14. Ambient air and average daily temperatures, Experiment Set 1, Trial 7.

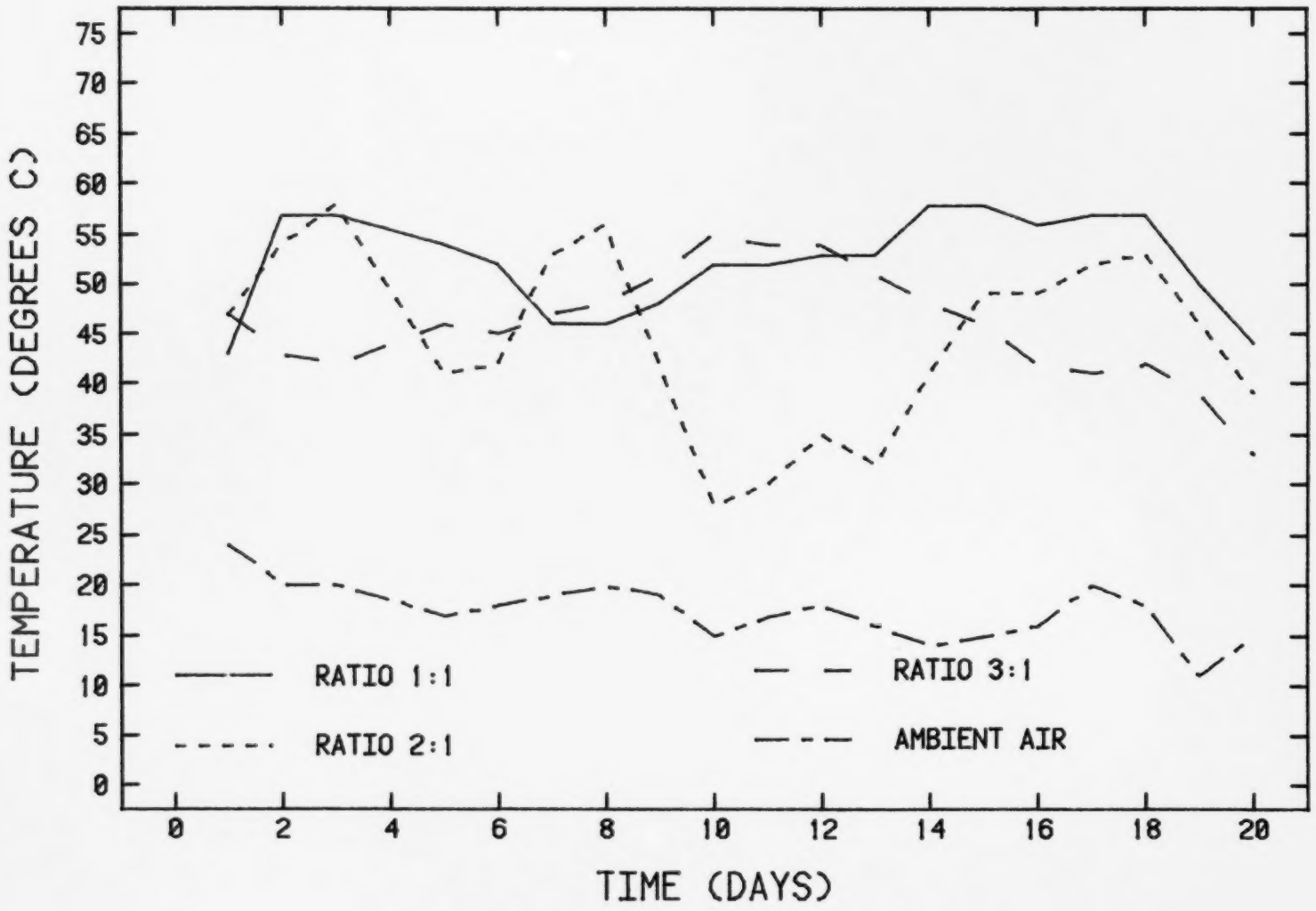

Figure 15. Ambient air and average daily temperatures, Experiment Set 1, Trial 8.

A temperature profile was observed in the composting mass, highest at the bottom and lowest at the top. This was due to cool ventilation air entering the composting vessels at the top and warmed exhaust air exiting from the bottom.

Composting Performance

Although Experiment Set 1 demonstrated that thermophilic composting can be conducted using (only) shredded rubber chips and dewatered raw primary sludge, the composting process proceeded under less than optimal conditions and produced undesirable odors and handling difficulties. The major problems were the high initial moisture content and the balling of sludge particles during mixing. These problems resulted in anaerobic conditions in which objectionable odors were produced. In addition, excess nitrogen was converted to ammonia and vented to the atmosphere as a result of the low C/N ratio. The porosity of the rubber chip and sludge mixtures were all acceptable and did not limit the composting process. Average porosities of 45.8, 47.0, and 49.5 percent were measured for 2:1 mixtures of the small, medium, and large size chips with raw primary sludge, respectively.

Rubber chips could not absorb sufficient water from the sludge to lower the moisture content into the 50 to 60 percent optimum range nor prevent the formation of sludge balls. Moisture is absorbed by shredded rubber only on the surface. Uncovered wet chips could potentially contribute water to the composting mixture, further increasing the moisture content and adversely affecting compost performance.

Sludge balls that formed while mixing were difficult to break during screening. This problem became more severe when the compost was dry. The condition resulted in poor screening efficiency which also occurred when wet compost was screened.

The blower operating time was recorded for use as an indicator of composting performance. During the initial stage of the composting process, aeration increased as a result of the rapid multiplication of the microbiological population. As the experiment progressed, the blower operating time decreased. However, these results were not considered a quantitative measure of biological activity since the ability to cool the compost mass was dependent on a number of undefined parameters including: relative humidity, ambient temperature, evaporation, sludge surface area, heat transfer efficiency, and resistance to air flow. Therefore, blower operating time was only used as a qualitative indicator of performance.

Comparison of the blower operating times for the three chip sizes shows no distinct pattern between the treatment and the amount of aeration (see Figures 16, 17, 18, and 19). Trial 1 was not graphed because there was only one time clock controlling a blower which ventilated all three boxes equally. These graphs illustrate the high level of activity of the raw primary sludge. Occasionally, the blowers ran continuously for an entire day. The lowest aeration rate, usually at the end of the experiments, corresponded to time clock controlled ventilation at a rate of 31.2 m^3/hr-dmt (1000 ft^3/hr-dt).

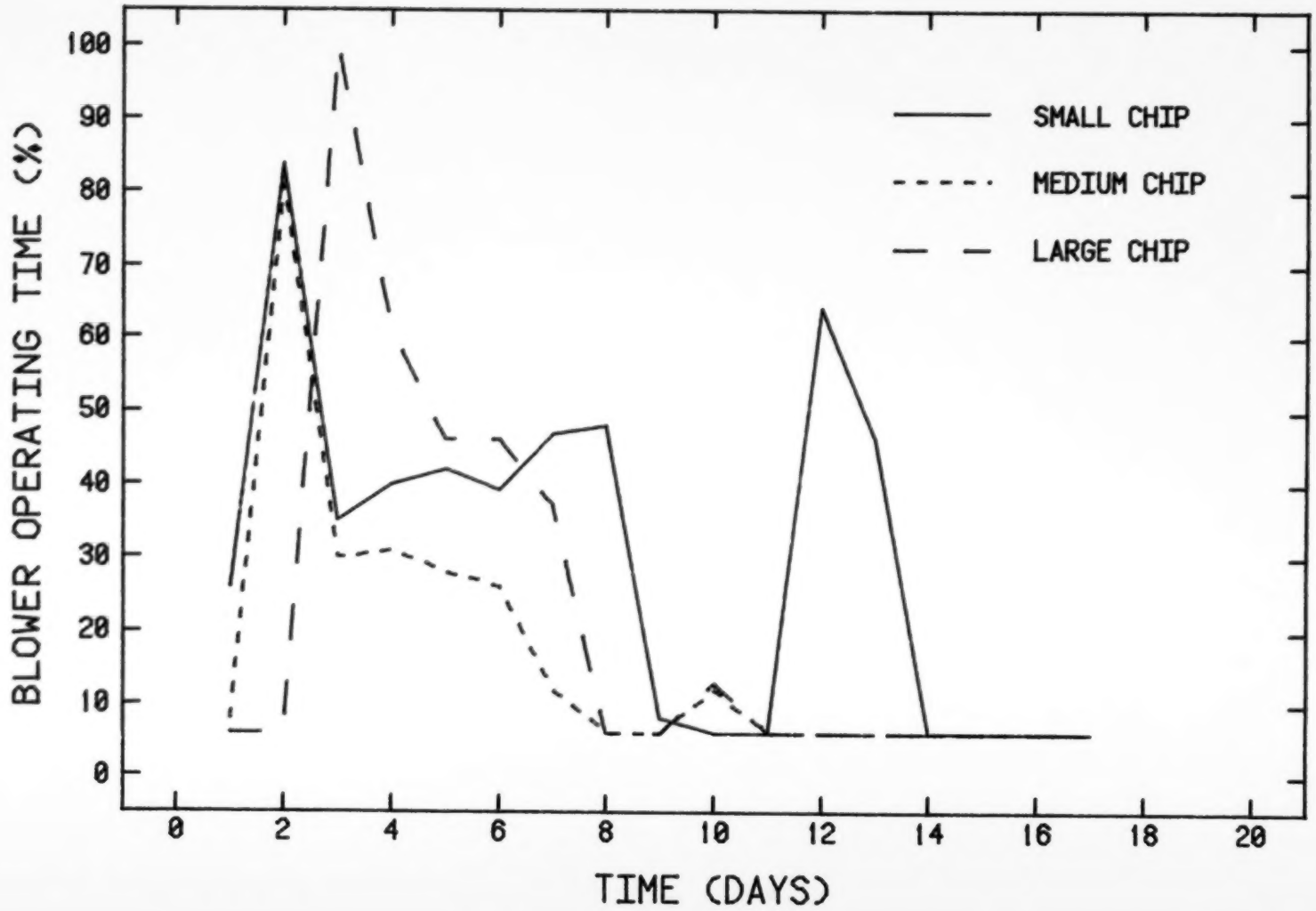

Figure 16. Total daily aeration blower operating time, Experiment Set 1, Trial 2.

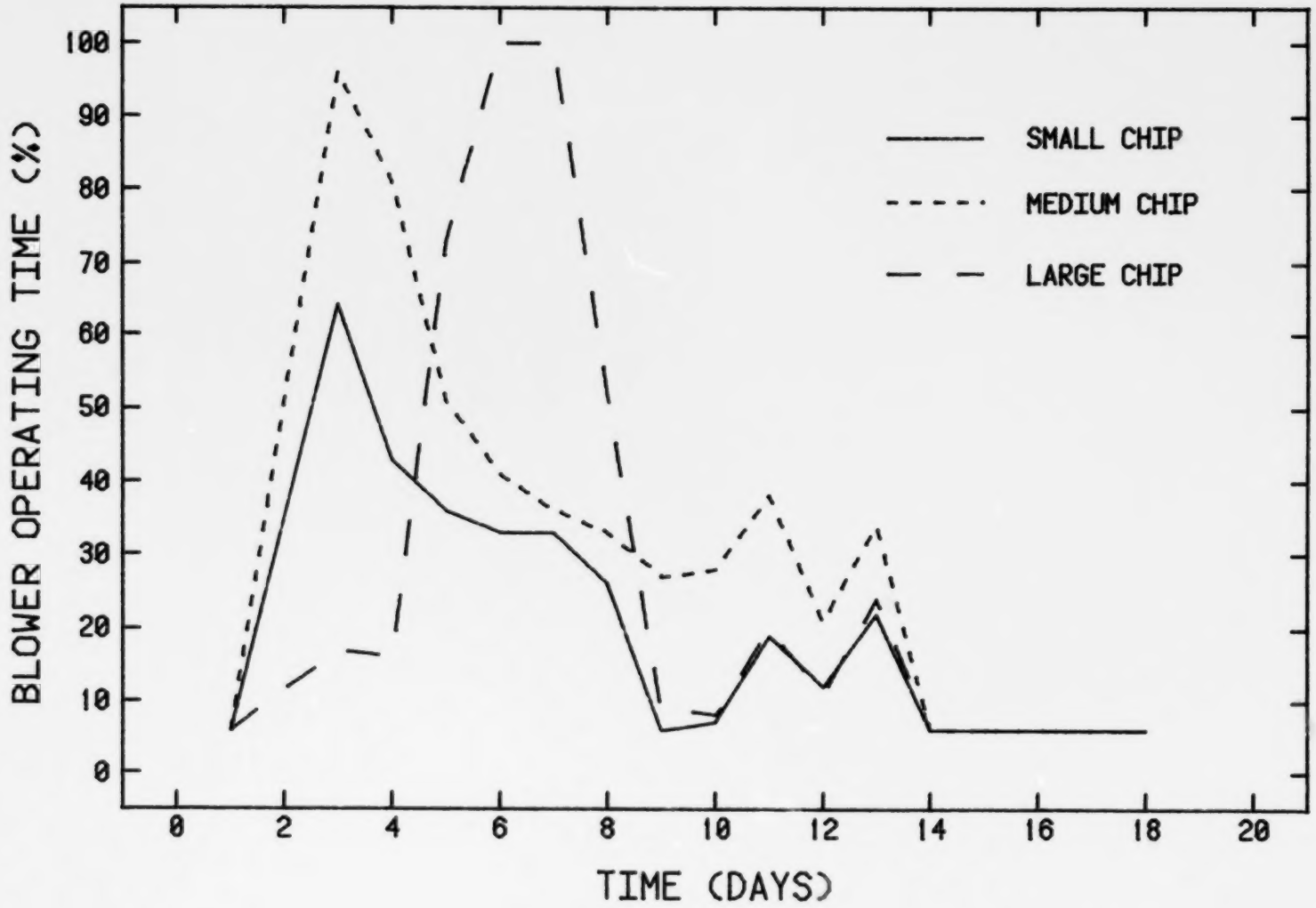

Figure 17. Total daily aeration blower operating time, Experiment Set 1, Trial 3.

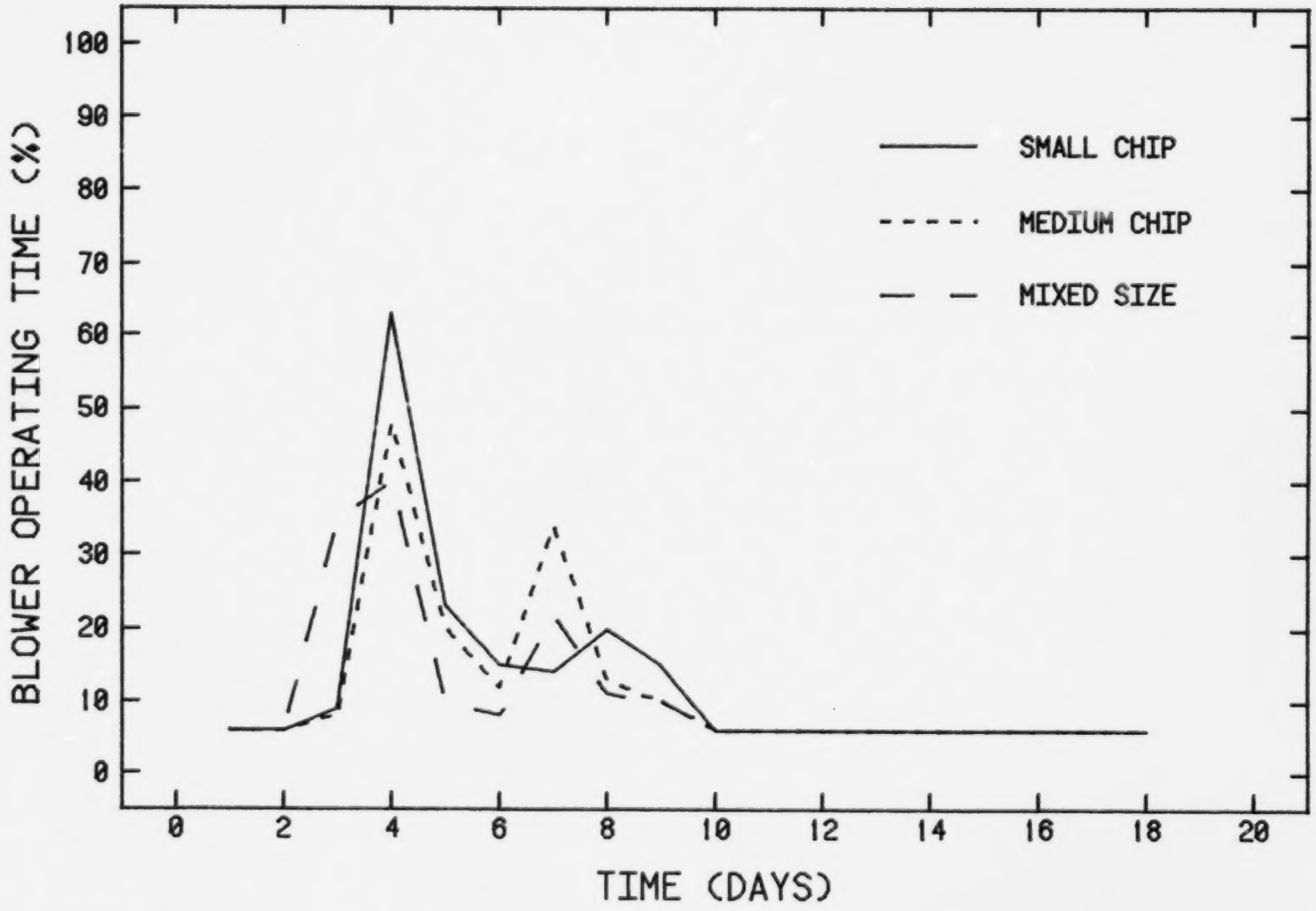

Figure 18. Total daily aeration blower operating time, Experiment Set 1, Trial 4.

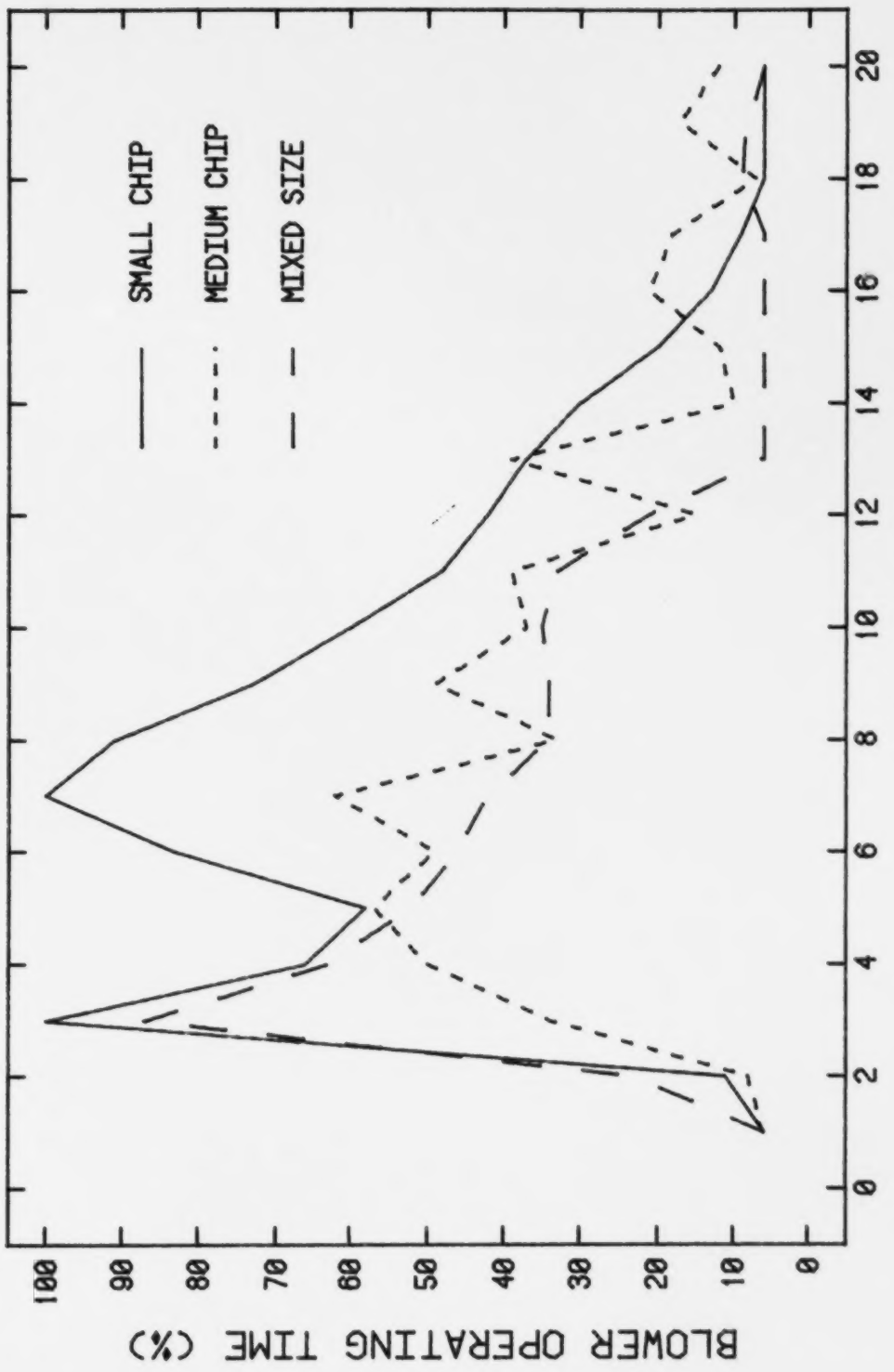

Figure 19. Total daily aeration blower operating time, Experiment Set 1, Trial 5.

The expected trend of blower operating time increasing with increasing mix ratio is displayed for Trials 6, 7, and 8 in Figures 20, 21, and 22. The horizontal line in Figure 20 represents time clock controlled ventilation for the 1:1 mix ratio which resulted when the thermostat malfunctioned. This line should not be used for comparisons. In all cases the 3:1 mix ratio had the shortest blower operating times.

Screening Efficiency

A rotary trommel screen manufactured by Royer Foundry and Machine Company with a 1.27 cm (1/2") mesh opening was used to recover the shredded rubber from the compost. Since the shredded rubber was initially screened before use in the composting experiments, no fine rubber particles were present. This resulted in a screened compost free of rubber particles.

The trommel screen was effective in removing the compost from the shredded rubber. Some carryover of compost in the screened rubber was evident. However, the amount of carryover was highly moisture dependent. The least amount of carryover resulted from the compost with a moisture content of 40% or less. Wet composts exceeding approximately 50% moisture were difficult to screen and produced a high percentage of carryover. This was in agreement with earlier testing of composting screens by Higgins et al. (11).

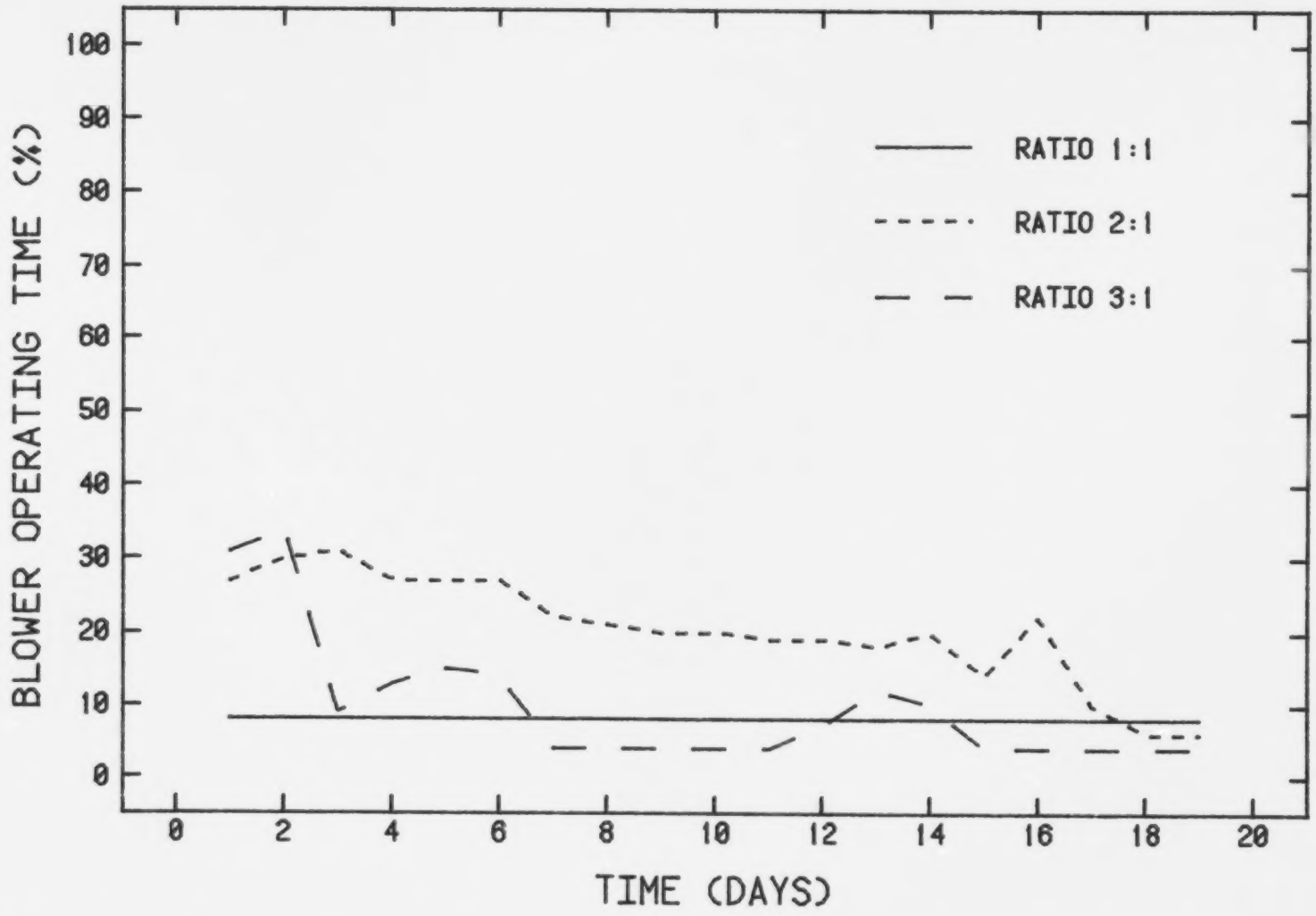

Figure 20. Total daily aeration blower operating time, Experiment Set 1, Trial 6.

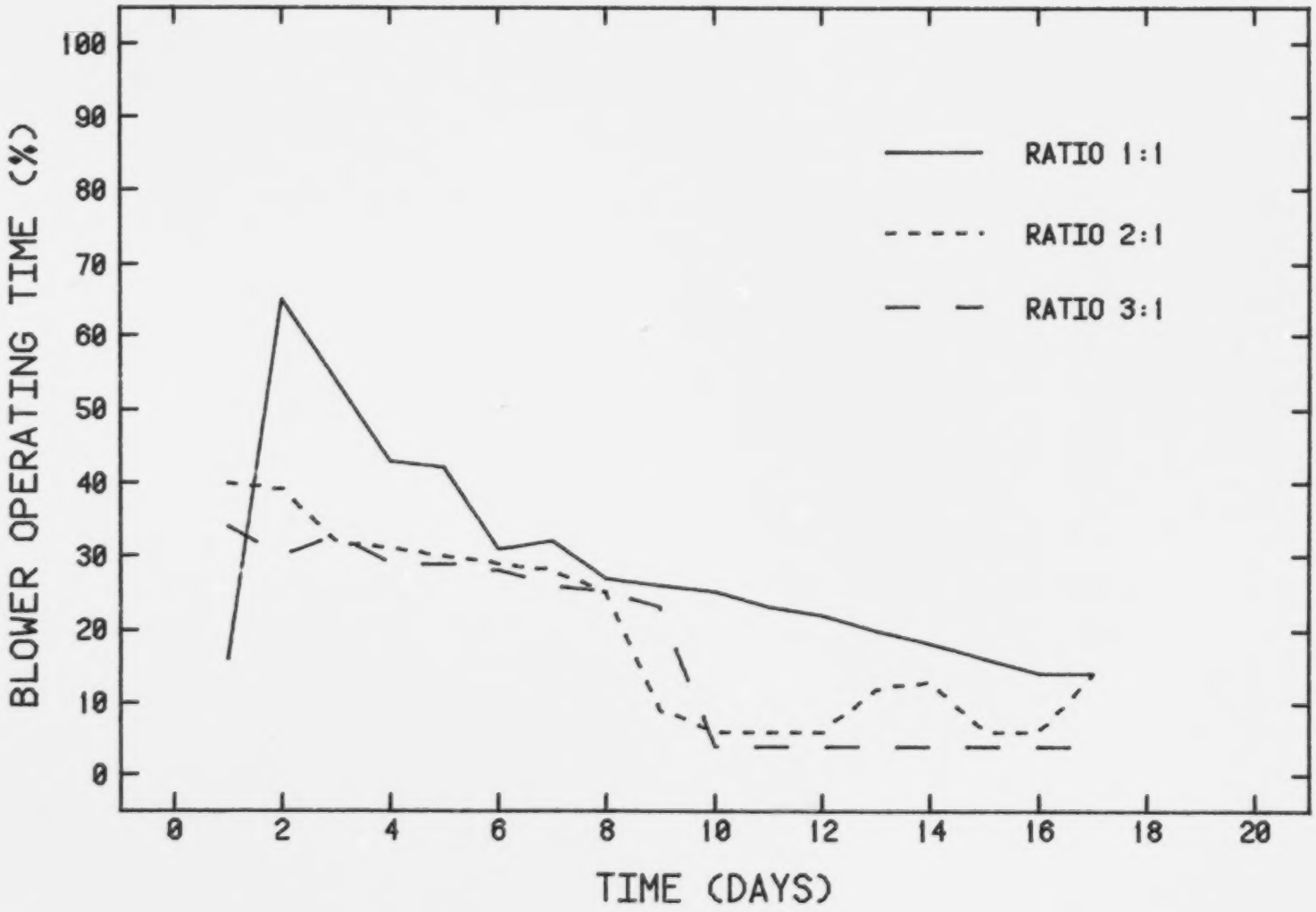

Figure 21. Total daily aeration blower operating time, Experiment Set 1, Trial 7.

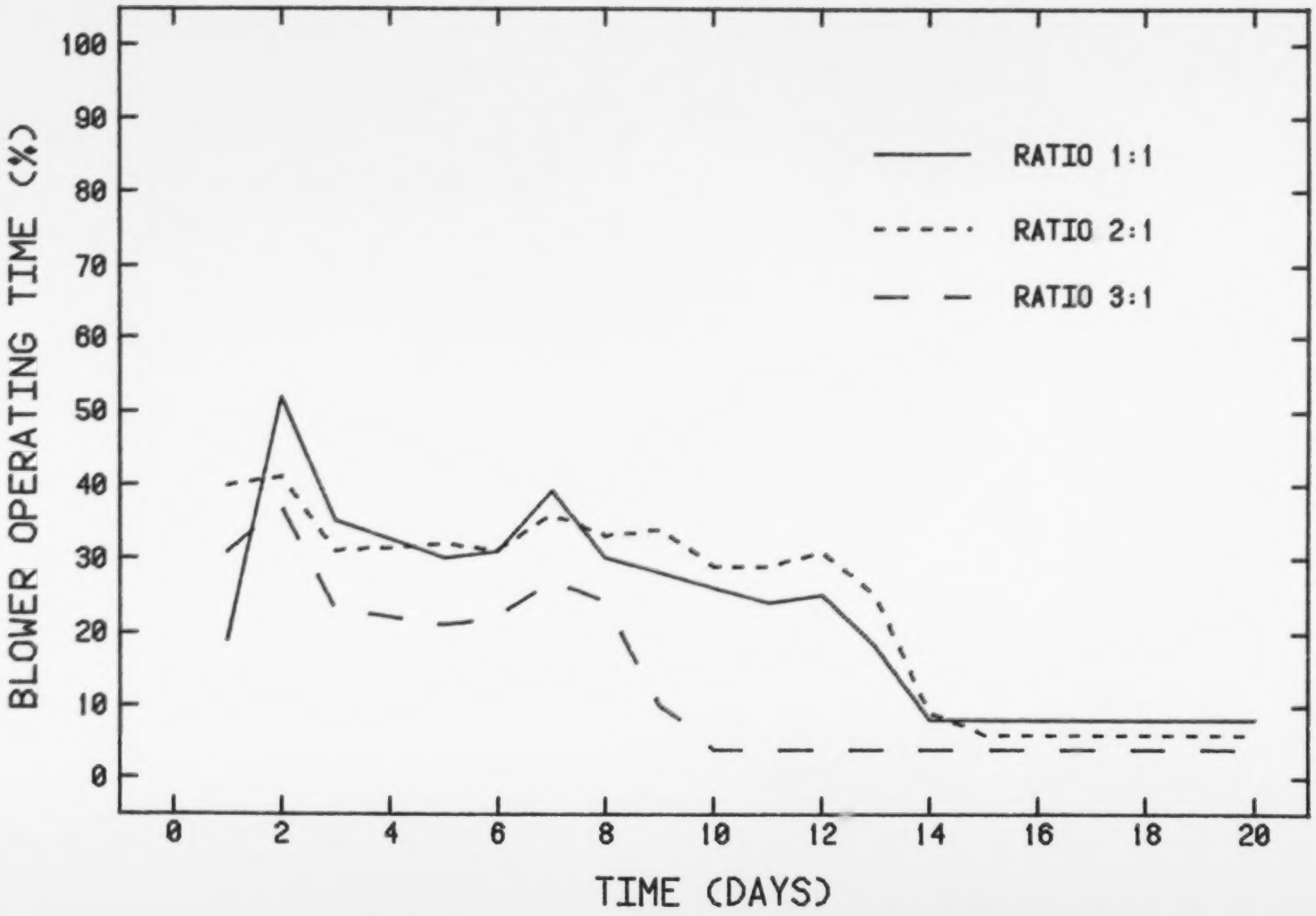

Figure 22. Total daily aeration blower operating time, Experiment Set 1, Trial 8.

Summary of Experiment Set 1

Based on this set of experiments, the following conclusions were reached:

1. The optimum size bulking agent was the small (1.27-2.54 cm) size rubber chip;

2. The optimum rubber chip to sludge mix ratio was determined to be 2:1;

3. The set point composting temperature (55°C) was usually maintained for dewatered raw primary sludge bulked with shredded rubber;

4 Amendments were needed to lower the initial moisture content of rubber chip and primary sludge mixtures to prevent the formation of sludge balls and anaerobic composting;

5. Since amendments were needed for primary sludge, they would also be needed for anaerobically digested sludge and biological sludge which have lower energy values and total solids content;

6. Shredded rubber tires were found to contribute zinc (Zn) and iron (Fe) to the compost; and

7. The contribution of zinc and iron to the compost decreased with repeated recycling (5 cycles).

EXPERIMENT SET 2, RAW PRIMARY SLUDGE PLUS AMENDMENTS

For Experiment Set 2, raw primary sludge was mixed with an amendment and bulked with the small size rubber chip. Two amendments were used; sawdust for Trial 1 and recycled compost for Trial 2. The sawdust was a mixture of sawdust and (up to 9.5 mm curled) shavings. The sawdust (mostly oak) was kiln dried to 5-7 percent moisture content and had a bulk weight of approximately 285 kg/m^3 (480 lb/yd^3). Screened compost was stored under an enclosure and was turned to promote drying.

Table 11 shows that by adding an amendment to the raw sludge, the moisture content of the initial mixture was lowered into the 50 to 60 percent optimum range for both trials. In addition, by adding sawdust (Trial 1), the C/N ratio was also increased into the optimum range (from 13.6 to 26.6). This combination of reducing moisture content and increasing the C/N ratio produced a dry screenable compost with no objectionable odors during the compost process. Adding recycled compost to the sludge did not increase the C/N ratio nor eliminate composting odors. A comparison of the C/N ratios of the initial mixture and the screened compost shows that during the sawdust trial the C/N ratio decreased, while the C/N ratio remained unchanged for the trial using recycled compost.

Volatile solids content and total carbon content were lower in the initial mixture than the raw sludge when recycled compost was added. This was expected due to the low organic matter and carbon content of the compost, which subsequently had a diluting effect on these two parameters in the initial mixture. The volatile solids content of the initial mixture and the compost remained high due to the addition of sawdust. Total carbon content displayed a similar pattern for the sawdust trial.

The average daily temperatures at the center of each composting vessel were plotted, along with the average daily ambient temperature, in Figures 23 and 24. For both trials, and all replicates, a temperature of 55°C was reached. Figure 23 shows that the thermostats maintained composting temperatures close to the 55°C set point for the entire experiment when sawdust was the amendment. The plotted composting temperatures for the three replications were also very similar for Trial 1. Temperatures were higher for Trial 2 (recycled compost); but they showed greater fluctuation and variation among the three replicates. The aeration blower cycle times for these two trials show that the blowers were on for a high percent of the time. (see Figures 25 and 26).

Summary of Experiment Set 2

The conclusions for this set of experiments were:

1. The set point composting temperature (55°C) was maintained for primary treatment sludge mixed with sawdust and recycled compost when bulked with shredded rubber;

2. Lowering the initial moisture content and increasing the C/N ratio eliminated odors and screening problems;

TABLE 11. MEAN COMPOSITION OF RAW PRIMARY SLUDGE, SLUDGE AND AMENDMENT MIXTURES, AND COMPOST SAMPLES FOR EXPERIMENT SET 2*

Parameter	Trial	Raw ‡ Sludge	Initial Mixture#	Compost Replicate 1	Compost Replicate 2	Compost Replicate 3
Moisture Content, (%)+	1	74.0	57.2	26.9	22.4	23.7
	2	75.3	56.5	28.5	39.8	29.4
Volatile Solids Content, (%)**	1	87.4	86.5	84.2	83.1	83.2
	2	82.7	63.6	59.6	62.6	59.5
Total Carbon Content, (%)**	1	35.3	37.3	31.2	31.2	31.0
	2	35.2	26.6	24.5	24.5	24.4
Total Nitrogen Content, (%)**	1	2.6	1.4	1.6	1.4	1.6
	2	3.1	2.4	2.2	2.1	2.1
C/N Ratio	1	13.6	26.6	19.5	22.3	19.4
	2	11.4	11.1	11.1	11.7	11.6

* Rubber chip to raw primary sludge to amendment mix ratio of 2:1:1 amendments were sawdust for Trial 1 and recycled compost for Trial 2

\# Rubber chips removed prior to laboratory analysis

\+ Percent wet mass basis

** Percent dry mass basis

‡ Measured before mixing

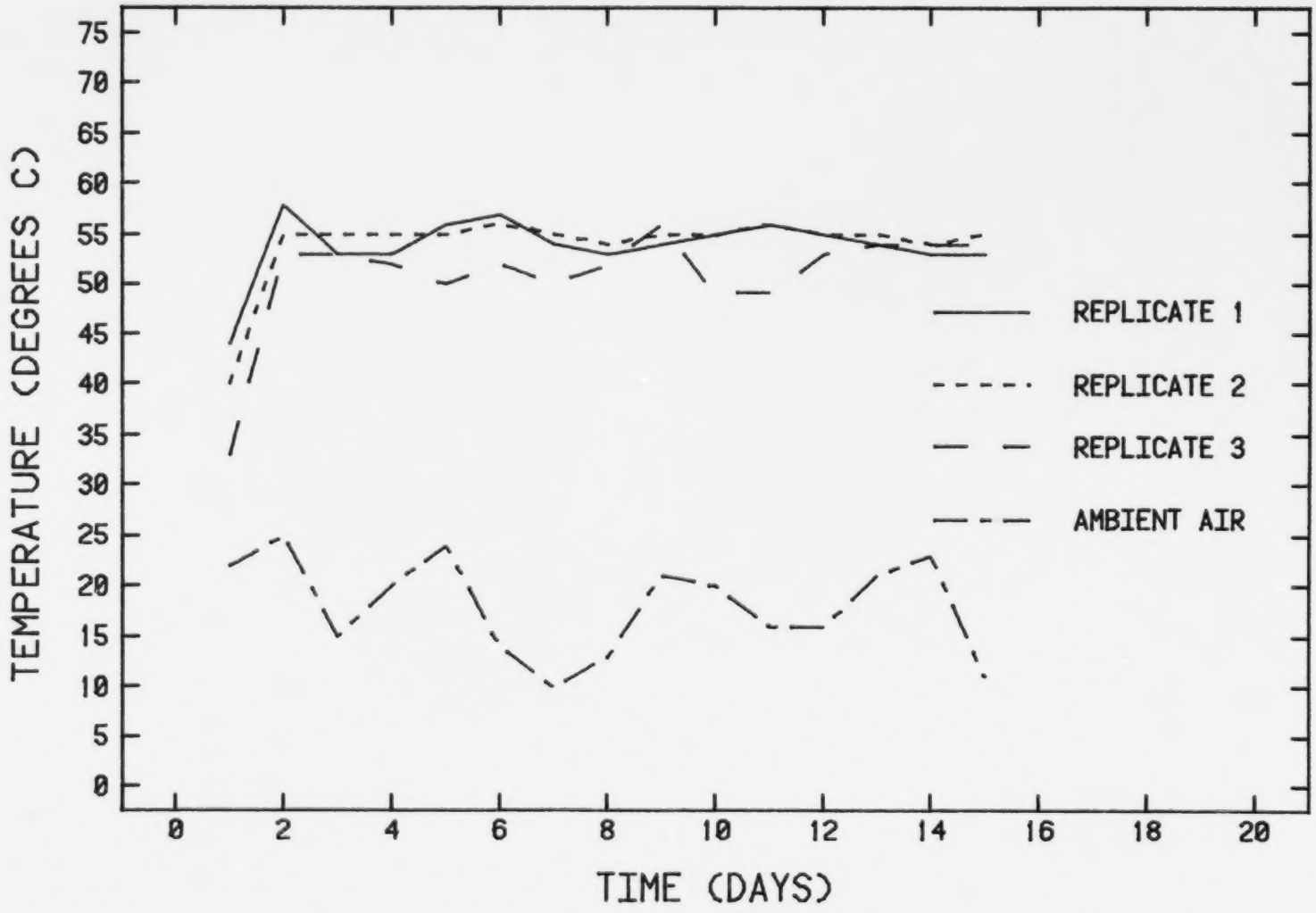

Figure 23. Ambient air and average daily temperatures, Experiment Set 2, Trial 1.

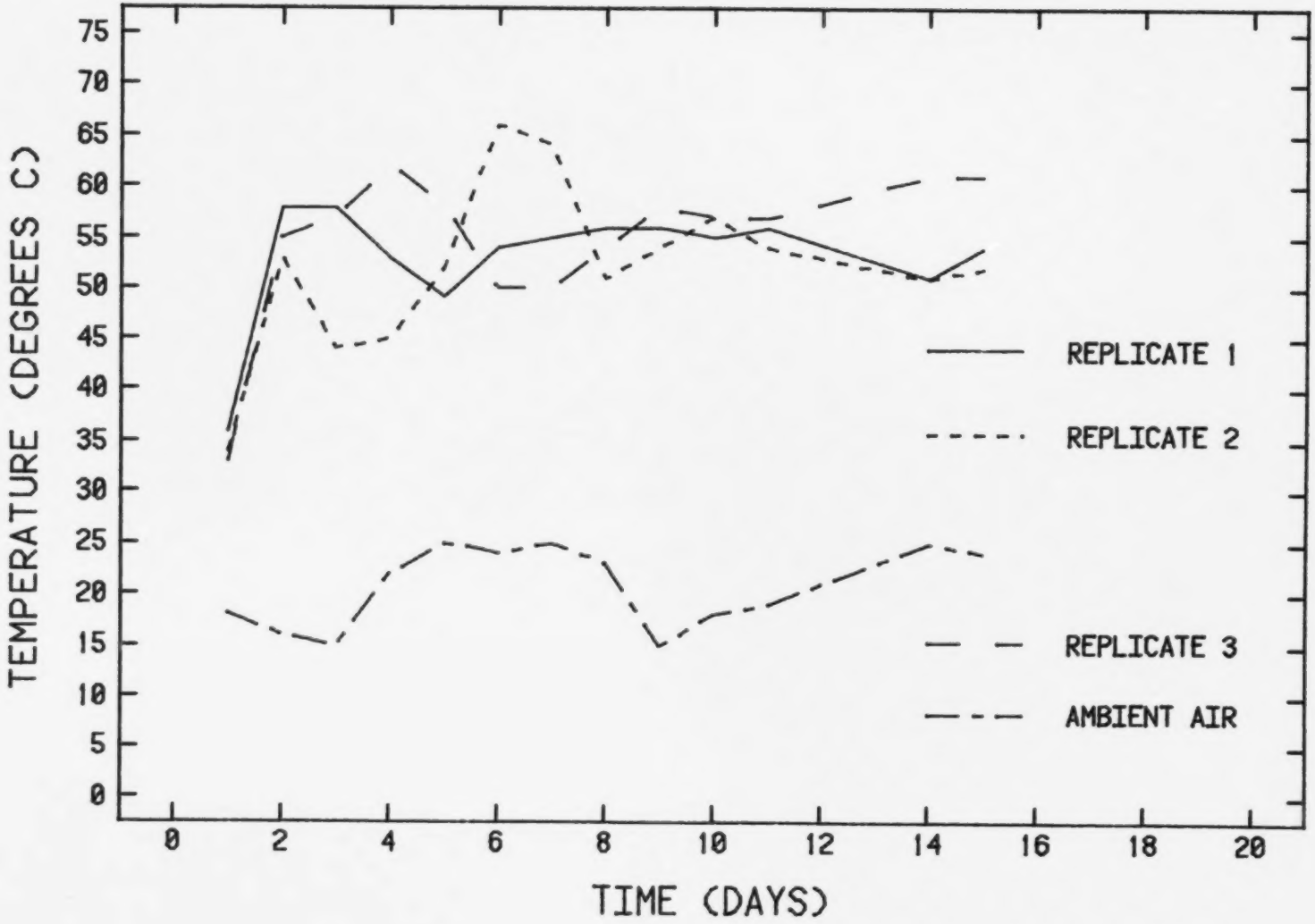

Figure 24. Ambient air and average daily temperatures, Experiment Set 2, Trial 2.

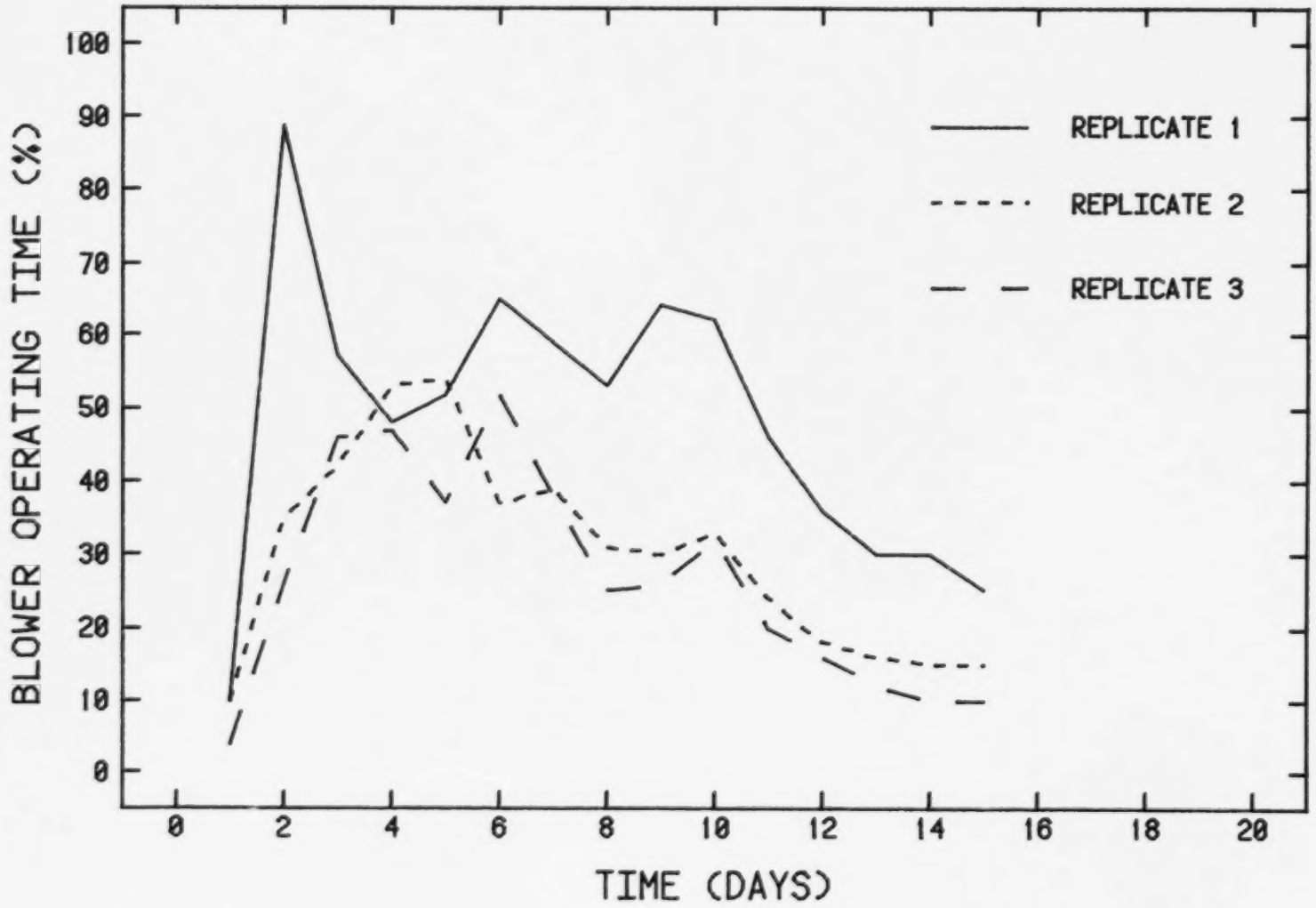

Figure 25. Total daily aeration blower operating time, Experiment Set 2, Trial 1.

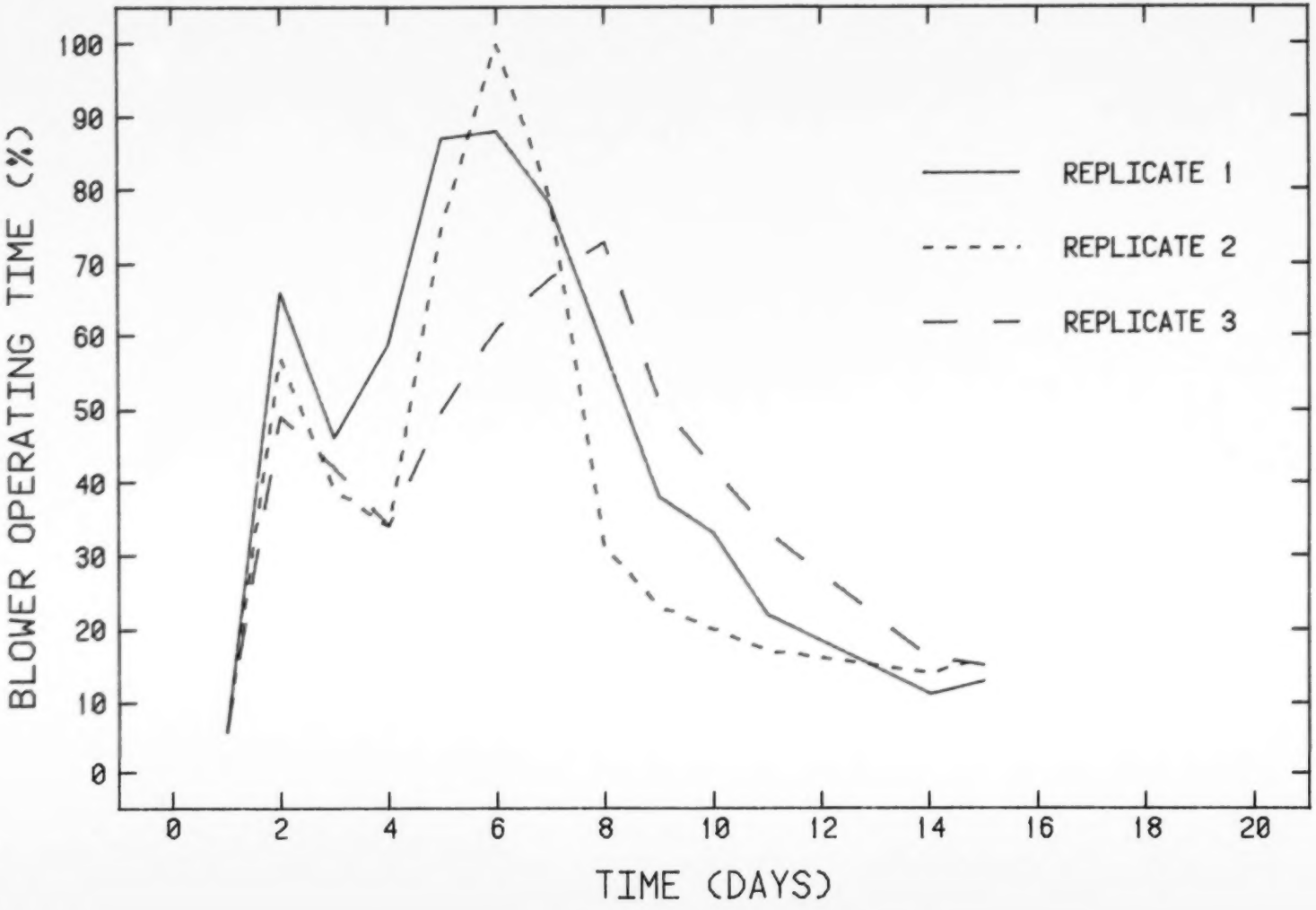

Figure 26. Total daily aeration blower operating time, Experiment Set 2, Trial 2.

3. A carbon source and moisture absorbing amendment had to be added to achieve optimum conditions; and

4. Of the two amendments tested, sawdust was superior to recycled compost.

EXPERIMENT SET 3, ANAEROBICALLY DIGESTED SLUDGE PLUS AMENDMENTS

For Trial 1 of Experiment Set 3, sawdust was mixed with anaerobically digested sludge and the small size rubber chip. The amendment for Trial 2 was screened compost. The anaerobically digested sludge had a moisture content of approximately 82 percent wet basis (see Table 12). The amount of amendment required to lower the initial mixture into the 50 to 60 percent optimum range was calculated to be approximately equal to the volume of sludge. The rubber chip to sludge to amendment mix ratio was 2:1:1 for both trials. This mix ratio lowered the moisture content into the desired range for Trial 2, but not for Trial 1. However, Trial 1 produced drier compost than Trail 2 due to the addition of moisture absorbing sawdust. There were no problems screening the compost from Trial 1. The compost from Trial 2 was wet and formed balls during unloading and screening. This resulted in a high percentage of compost staying with the rubber chips. When a wet compost was encountered, approximately one-third to one-half the entire mass was screened to obtain samples for laboratory analysis. Unloading was from all layers. The remaining mass was allowed to dry and then screened at a later date. This practice minimized the amount of compost carryover in the screened rubber chips.

As a result of digestion, anaerobically digested sludge has a high total nitrogen content and a low carbon content which yields a low C/N ratio (see Table 12). This is not favorable for composting. Therefore, a carbon source is essential. As expected, the addition of sawdust to the anaerobically digested sludge increased the volatile solids content, total carbon content, and C/N ratio of the initial mixture. These parameters remained high in the screened compost. Recycled compost did not supply enough carbon for effective composting. Adding recycled compost to the anaerobically digested sludge decreased the volatile solids content. The test with recycled compost produced odors, but not as strong as those produced during Experiment Set 1 using raw primary sludge. When sawdust was used as an amendment, odors were not a problem. Also, Trial 2 did not compost well or uniformly. During unloading, ammonia gas was detected qualitatively and numerous pockets of wet uncomposted sludge were found.

Figures 27 and 28 shows the average temperature at the center of each composting vessel. These figures show that 55°C composting temperatures were reached for all replicates. Trial 1, with sawdust as the amendment, had less variation among the replicates as the average temperatures were maintained close to 55°C. Trial 1 (using sawdust) showed much lower blower cycle times than Trial 2 (see Figures 29 and 30). The sawdust trial also had lower blower operating time than the raw primary sludge with sawdust trial. Trial 2 (recycled compost) showed high variability among the three replicates.

TABLE 12. MEAN COMPOSITION OF ANAEROBICALLY DIGESTED SLUDGE, SLUDGE AND AMENDMENT MIXTURES, AND COMPOST SAMPLES FOR EXPERIMENT SET 3*

Parameter	Trial	Raw‡ Sludge	Initial Mixture#	Compost Replicate 1	Compost Replicate 2	Compost Replicate 3
Moisture Content, (%)+	1	81.9	62.8	46.2	45.2	48.5
	2	81.6	55.0	50.5	50.0	50.2
Volatile Solids Content, (%)**	1	62.2	76.3	75.8	73.1	75.5
	2	60.4	55.1	48.5	50.1	52.0
Total Carbon Content, (%)**	1	14.4	32.6	27.0	27.4	27.5
	2	16.9	20.4	16.9	17.3	18.0
Total Nitrogen Content, (%)**	1	4.8	2.4	2.1	2.4	2.5
	2	4.5	2.4	2.1	2.5	2.5
C/N Ratio	1	3.0	13.6	12.8	11.4	11.0
	2	3.8	8.5	8.0	6.9	7.2

* Rubber chip to anaerobically digested sludge to amendment mix ratio of 2:1:1 amendments were sawdust for Trial 1 and recycled compost for Trial 2

\# Rubber chips removed prior to laboratory analysis

\+ Percent wet mass basis

** Percent dry mass basis

‡ Measured before mixing

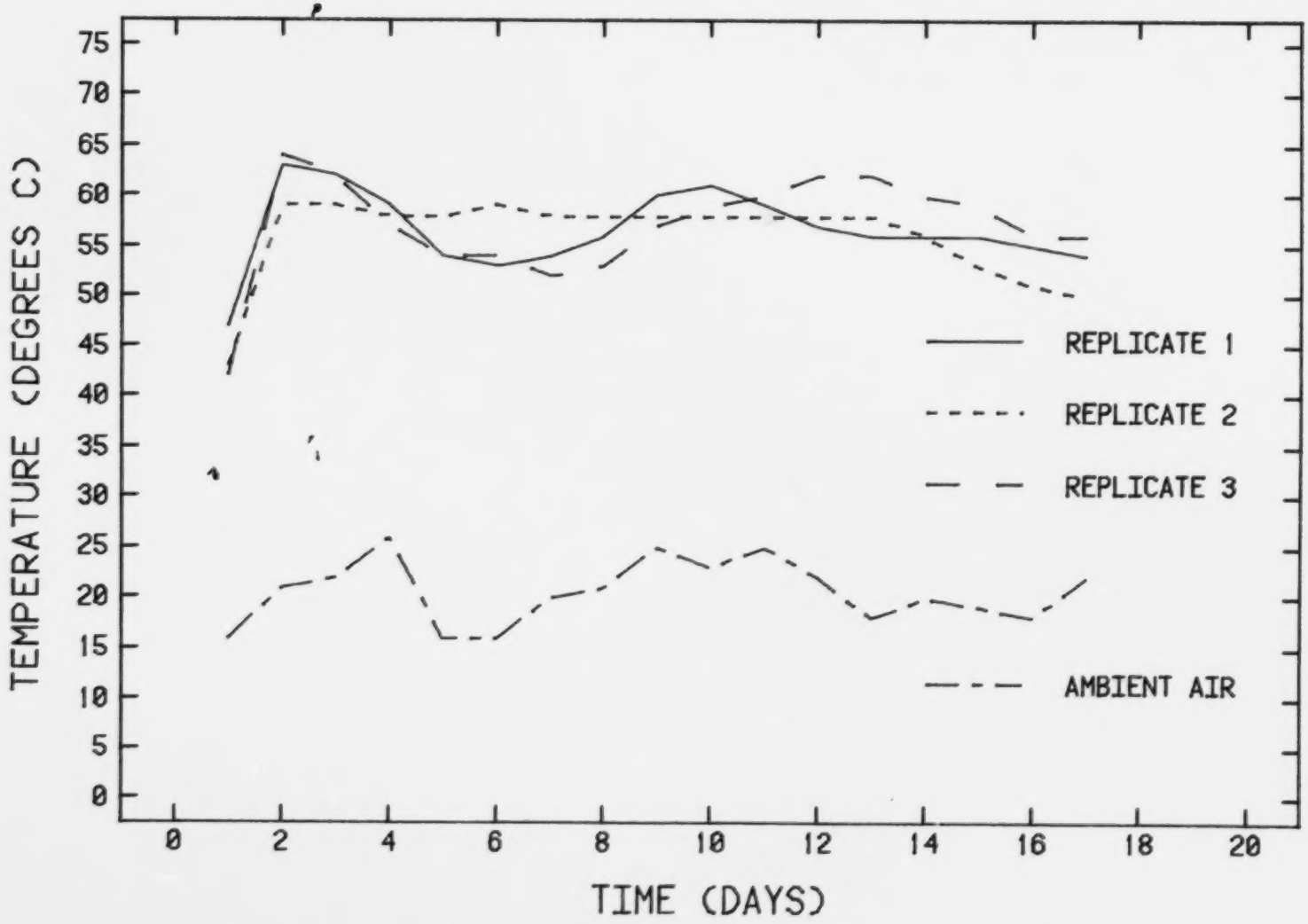

Figure 27. Ambient air and average daily temperatures, Experiment Set 3, Trial 1.

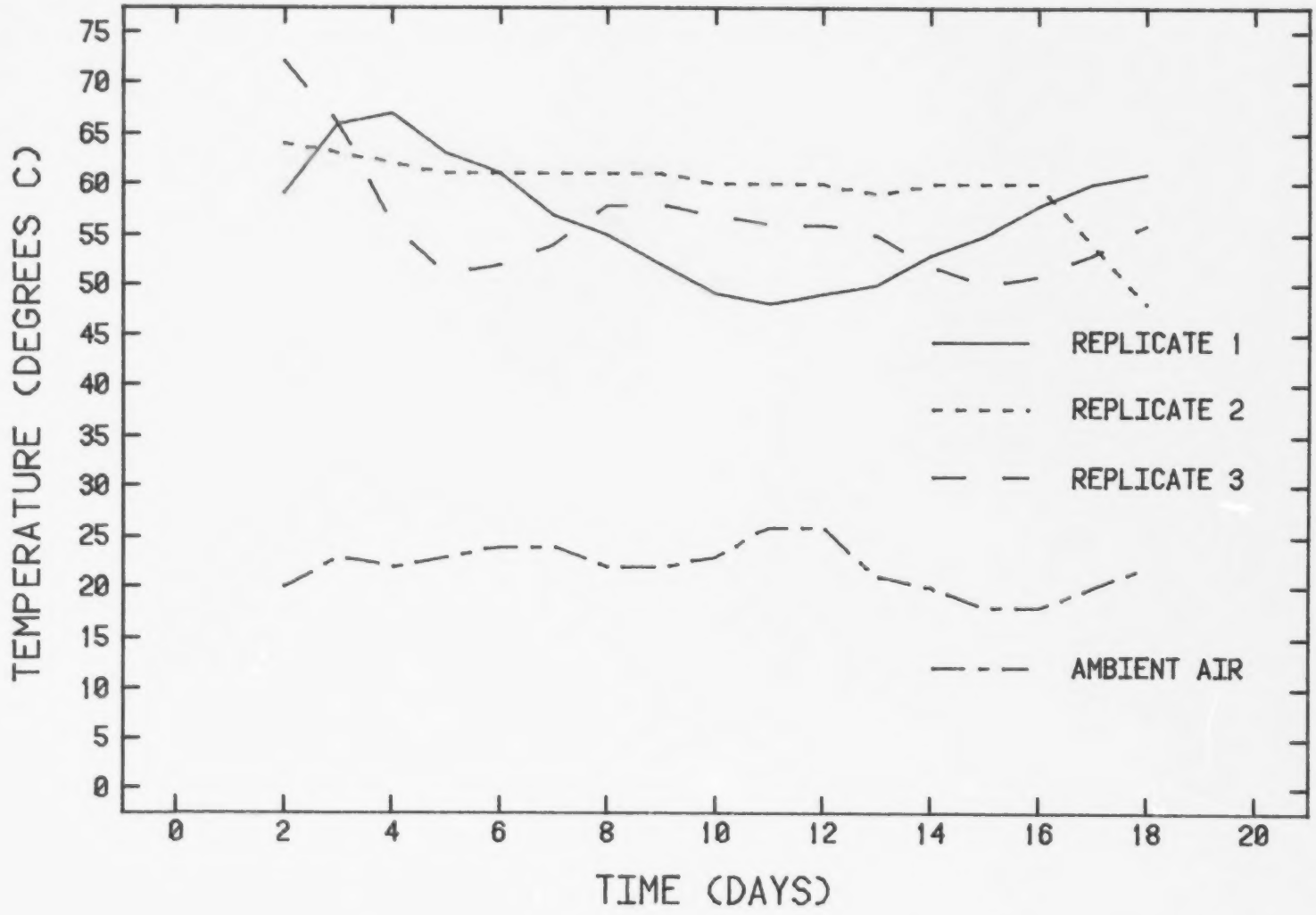

Figure 28. Ambient air and average daily temperatures, Experiment Set 3, Trial 2.

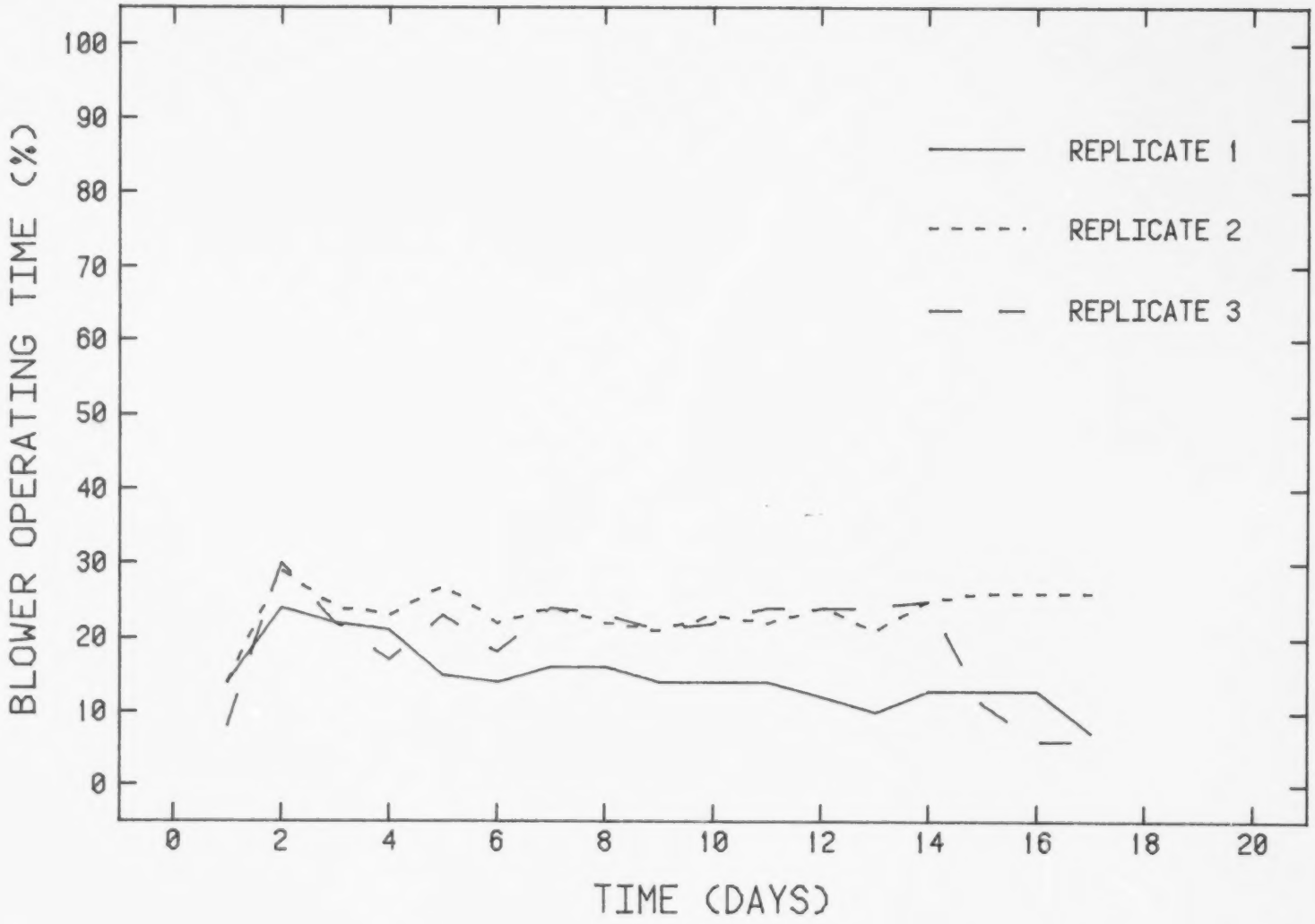

Figure 29. Total daily aeration blower operating time, Experiment Set 3, Trial 1.

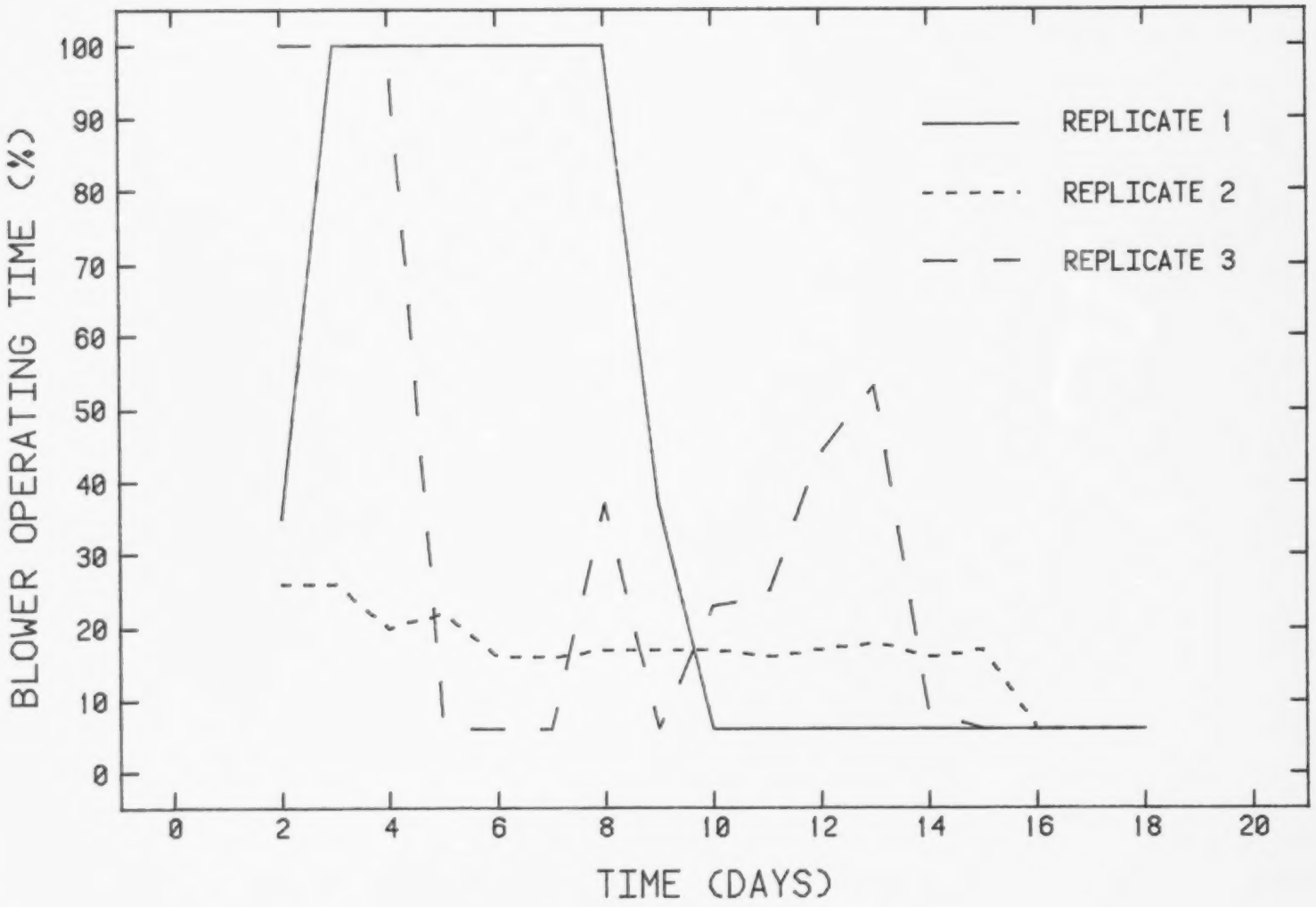

Figure 30. Total daily aeration blower operating time, Experiment Set 3, Trial 2.

Summary of Experiment Set 3

Based on this set of experiments the following conclusions were reached:

1. The set point composting temperature of 55°C was maintained for anaerobically digested sludge and shredded rubber mixtures amended with sawdust and recycled compost;

2. A carbon source and moisture absorbing amendment must be added to compost anaerobically digested sludge; and

3. Of the two amendments tested, sawdust was effective and recycled compost ineffective.

EXPERIMENT SET 4, SECONDARY BIOLOGICAL SLUDGE PLUS AMENDMENTS

Secondary biological sludge was obtained and mixed with either sawdust (Trial 1) or recycled compost (Trial 2) for Experiment Set 4. The small size rubber chip was used. With a moisture content over 85 percent wet basis (see Table 13), the secondary biological sludge contained more water than both the primary and anaerobically digested sludges used earlier. As a result, the amount of amendment required to lower the initial moisture content was greater than for Set 3. For Set 4, the rubber chip to sludge to amendment mix ratio was 2:1:1.5. This ratio produced initial mixtures that had 56 to 57 percent moisture contents, but had different physical characteristics depending on which amendment was used. In Trial 1, the sawdust aided the mixing of the sludge and rubber chips. The mixture had a uniform consistency that was easy to handle. This was not the case when recycled compost was the amendment (Trial 2). The mixture with recycled compost appeared wet and was very sticky. The sludge formed balls and clumps during the loading phase of the experiment. This occurred in the mixer and in the conveyor used to load the compost vessels. The formation of sludge balls and clumps also contributed to composting odors.

As a result of treatment, secondary biological sludge like anaerobically digested sludge, has a high total nitrogen content and low carbon content. The resultant C/N ratio is low and a supplemental carbon source is necessary. Table 13 shows that the trial with sawdust increased the C/N ratio from 3.7 to 16.6, while the addition of recycled compost only increased the C/N ratio from 3.7 to 8.9.

During Trial 1, no odors were detected. This was due to the addition of the sawdust which: (1) lowered the moisture content into the optimal range; (2) provided carbon to adjust the C/N ratio; and (3) aided in mixing the sludge and rubber chips. Odors were detected during Trial 2; they were strongest during the first week of the experiment. These odors were not as strong and objectionable as those produced by composting raw primary sludge. The odors were present, even though the moisture content was in the optimal range, because the recycled compost did not prevent the formation of sludge balls and clumps, or provide sufficient carbon to adequately increase the C/N ratio.

TABLE 13. MEAN COMPOSITION OF SECONDARY BIOLOGICAL SLUDGE, SLUDGE AND AMENDMENT MIXTURES, AND COMPOST SAMPLES FOR EXPERIMENT SET 4*

Parameter	Trial	Raw ‡ Sludge	Initial Mixture#	Compost Replicate 1	Compost Replicate 2	Compost Replicate 3
Moisture Content, (%)+	1	85.7	57.4	35.6	37.9	32.4
	2	85.3	55.8	45.9	42.5	47.9
Volatile Solids Content, (%)**	1	72.8	79.3	71.9	77.1	77.7
	2	68.0	57.6	49.6	52.8	53.2
Total Carbon Content, (%)**	1	19.2	29.9	27.7	28.6	28.6
	2	16.9	20.4	16.9	17.3	18.0
Total Nitrogen Content, (%)**	1	5.2	1.8	1.8	2.2	2.2
	2	4.6	2.3	2.4	2.1	2.6
C/N Ratio	1	3.7	16.6	15.4	13.0	13.0
	2	3.7	8.9	7.0	8.2	6.9

* Rubber chip to biological sludge to amendment mix ratio of 2:1:1:5 amendments were sawdust for Trial 1 and recycled compost for Trial 2

\# Rubber chips removed prior to laboratory analysis

\+ Percent wet mass basis

** Percent dry mass basis

‡ Measured before mixing

The compost from Trial 1 was dry (32 to 38 percent moisture) and screened well. The compost from Trial 2 appeared wet. During unloading and screening the compost conglomerated which resulted in a high amount of screening carryover.

Average daily composting temperatures are plotted in Figures 31 and 32. Although the average daily temperature (measured in the center of the pile) did not reach 55°C for two replicates in Trial 1, they were above 50°C for the first 4 to 9 days. All three replicates in Trial 2 obtained 55°C composting temperatures. The aeration blower cycle times were low for both trials (see Figures 33 and 34), similar to the anaerobically digested sludge mixed with sawdust trial.

Summary of Experiment Set 4

The conclusions for Experiment Set 4 were:

1. The set point composting temperature (55°C) was usually maintained for secondary biological sludge and shredded rubber mixture amended with sawdust and recycled compost;

2. A carbon source and moisture absorbing amendment must be added to compost secondary biological sludge;

3. Both amendments adequately lowered the initial moisture content of the sludge;

4. The addition of sawdust aided in mixing the sludge and rubber chips and eliminated composting odors;

5. Recycled compost did not prevent the sludge from forming clumps during mixing and loading; and

6. Recycled compost did not supply ample carbon or prevent odors.

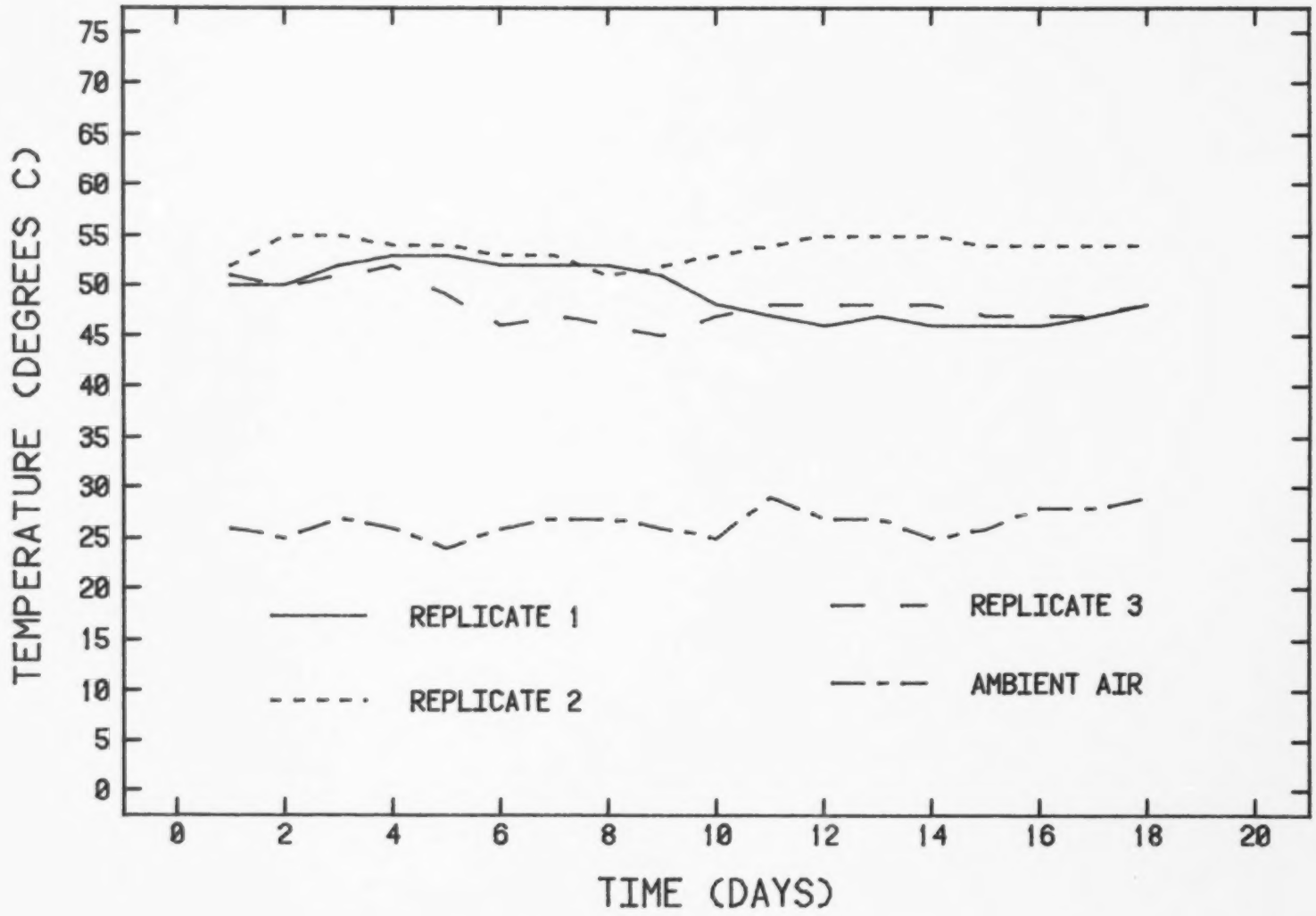

Figure 31. Ambient air and average daily temperatures, Experiment Set 4, Trial 1.

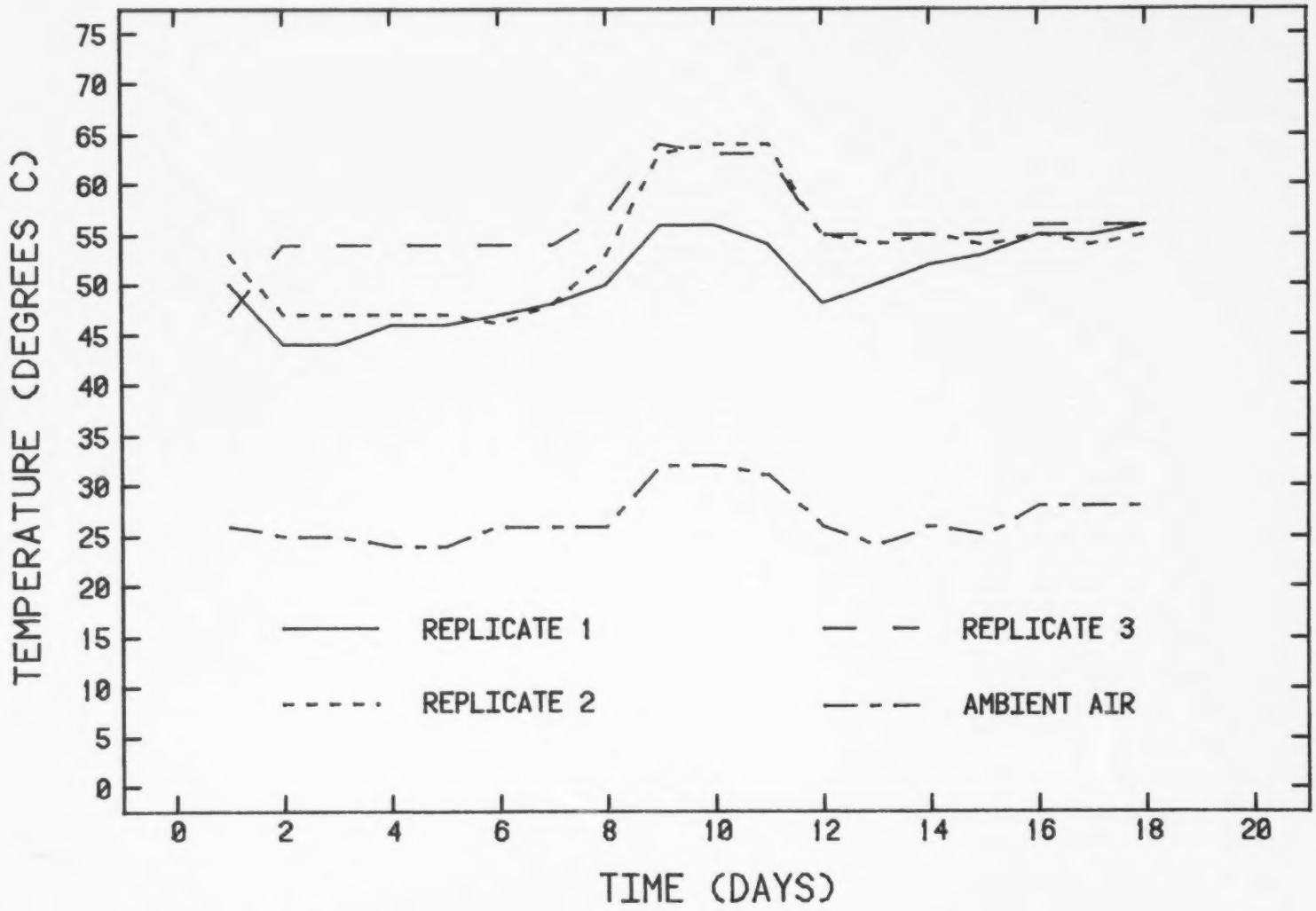

Figure 32. Ambient air and average daily temperatures, Experiment Set 4, Trial 2.

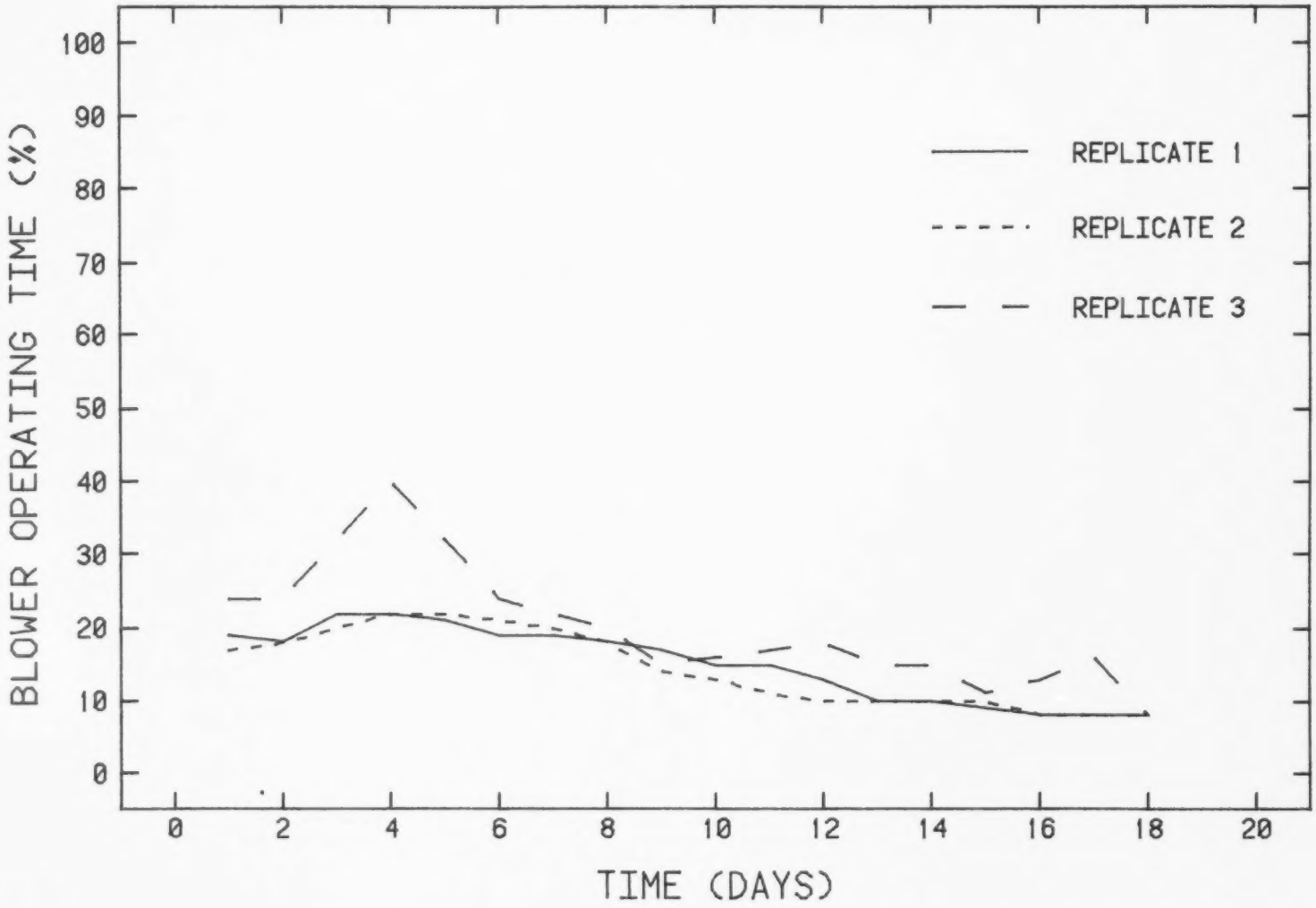

Figure 33. Total daily aeration blower operating time, Experiment Set 4, Trial 1.

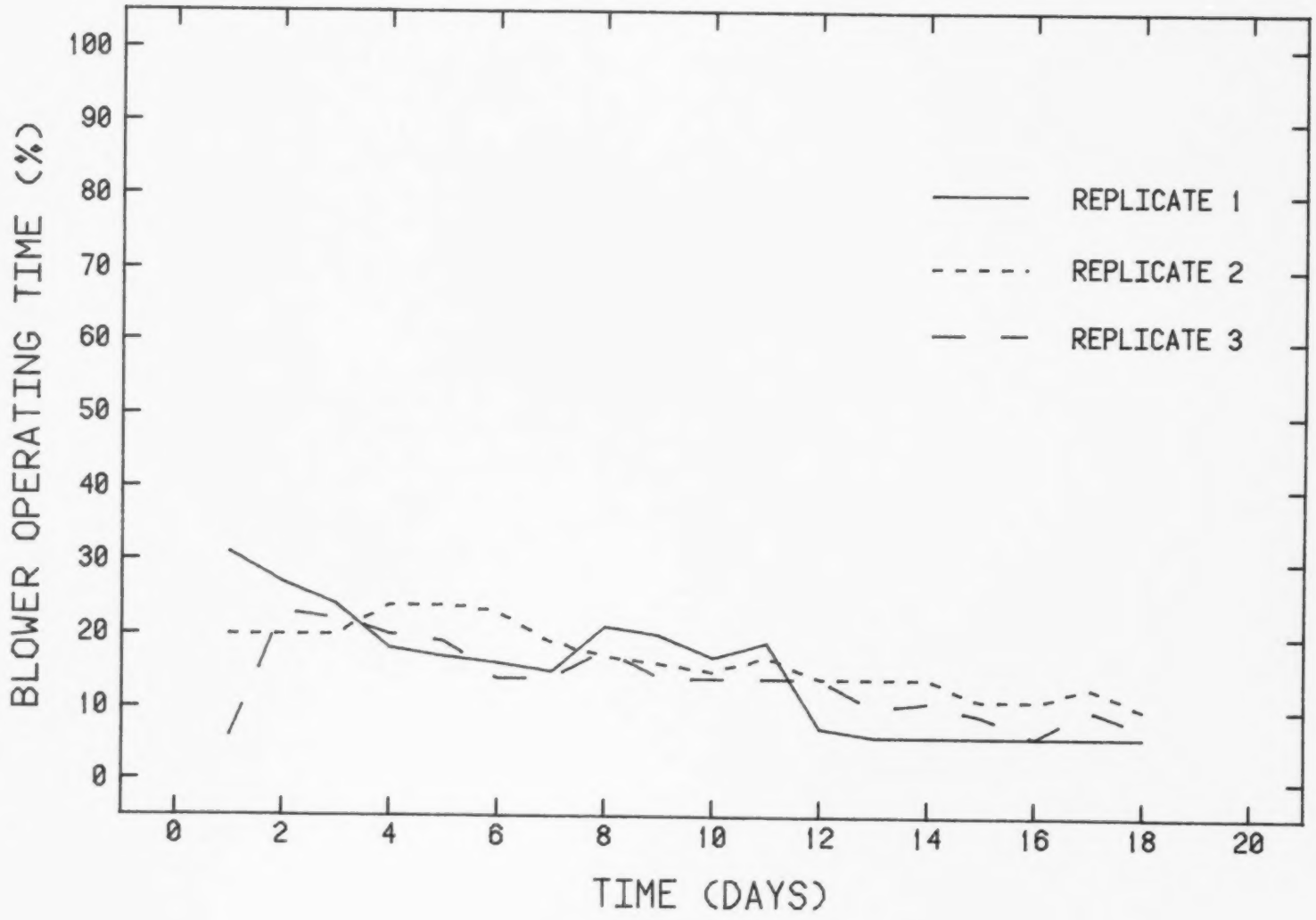

Figure 34. Total daily aeration blower operating time, Experiment Set 4, Trial 2.

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APPENDIX

PERCENT REDUCTION SAMPLE CALCULATIONS

Difficulties arose in determination of the percent reduction of volatile solids (VS), moisture content, or carbon content. Merely taking the mathematical difference of the initial and final percentages was incorrect. This was due to the method of calculating percentages; percentage is defined as:

$$\text{Percentage (\%)} = \frac{\text{Part}}{\text{Whole}} (100)$$

For example, suppose the total solids entering the digester was comprised of 80% volatile solids and 20% fixed (inert) solids and, after the reduction of volatile solids due to digestion, the solids leaving the digester contains 50% volatile solids.

Solids entering		Solids leaving	
VS	80%	VS	50%
Fixed Solids	20%	Fixed Solids	50%

Assuming that the fixed solids remain constant during the digestion or degradation process, there is an apparent contradiction when comparing the 20% fixed solids entering the digester and the 50% fixed solids leaving the digester. This contradiction is due to percentages which are based on two different wholes. The percent reduction in VS is not equal to (80% - 50%) = 30%. Sample calculations for the percent reduction in volatile solids content, moisture content, and carbon content follow.

VOLATILE SOLIDS (VS) CONTENT REDUCTION

Assume samples of sludge (initial) and compost (final) were analyzed:

Initial Moisture Content = 73.7% Initial VS = 79.8%
Final Moisture Content = 40.6% Final VS = 54.8%

Therefore, a 1.000 kg dry sample would contain:

Initial VS = 0.798 kg
Fixed Solids (inert) = 0.202 kg

Let, Y equal the (unknown) final mass of VS and X the (known) final VS percentage.

$$X = 54.8\% = 0.548$$

$$X = \frac{Y}{(Y + \text{fixed solid})} = \frac{Y}{(Y + 0.202)}$$

$$X\,(Y + 0.202) = Y$$

$$X\,Y + X\,(0.202) = Y$$

$$Y - X\,Y = 0.202\,X$$

$$Y\,(1 - X) = 0.202\,X$$

$$Y = \frac{0.202X}{1 - X}$$

$$Y = \frac{(0.202)\,(0.548)}{1 - 0.548} = \frac{0.1107}{0.4520}$$

$$Y = 0.2449 \text{ kg}$$

$$\%\ \text{Reduction} = \frac{(\text{Initial}) - (\text{Final})}{(\text{Initial})}\,(100)$$

$$\%\ \text{Reduction} = \frac{0.798 - 0.2449}{0.798}\,(100) = 69.3 = 69\%$$

MOISTURE CONTENT REDUCTION

Assume samples of sludge (initial) and compost (final) were analyzed:

Initial Moisture Content = 73.7%	Initial VS = 79.8%
Final Moisture Content = 40.6%	Final VS = 54.8%

Therefore, a 1.000 kg wet sample would contain:

Initial mass of water	= 0.737 kg
Initial mass of Total Solids	= 0.263 kg
Initial mass of VS	= (0.263) (0.798) = 0.2099 kg
Fixed Solids (inert)	= (0.263 - 0.2099) = 0.0531 kg

Based on 69.3% reduction of VS:

$$(0.2099)\,(0.693) = 0.1455 \text{ kg of VS were decomposed.}$$

$$\text{Final VS} = 0.2099 - 0.1455$$
$$= 0.0644 \text{ kg}$$

Final Total Solids = 0.0644 + 0.0531
= 0.1175 kg

Let Y equal the (unknown) final mass of water and X the (known) final moisture content percentage.

$$X = 40.6\% = 0.406$$

$$X = \frac{Y}{(Y + \text{Final Total Solids})} = \frac{Y}{(Y + 0.1175)}$$

Solving for Y yields:

$$Y = \frac{(0.1175)\ (X)}{1 - X} = \frac{(0.1175)\ (0.406)}{1 - 0.406}$$

$$Y = 0.0803 \text{ kg}$$

$$\% \text{ Reduction} = \frac{(0.737 - 0.0803)}{0.737}\ (100)$$

$$\% \text{ Reduction} = 89.1 = 89\%$$

CARBON CONTENT REDUCTION

Assume samples of sludge (initial) and compost (final) were analyzed:

Initial Carbon Content = 35.9%	Initial VS = 79.8%
Final Carbon Content = 29.9%	Final VS = 54.8%

Therefore, a 1.000 kg dry sample would contain:

Initial	Volatile Solids	= 0.798 kg
	Fixed Solids	= 0.202 kg
	Total	= 1.000 kg

Initial	Carbon	= 0.359 kg
	Non Carbon VS	= (0.798 - 0.359) = 0.439 kg
	Fixed Solids	= 0.202 kg
	Total	= 1.000 kg

Based on 69.3% VS reduction, the final VS was (previously) calculated to be 0.2449 kg. The Final Total Solids is calculated:

$$\text{Final Total Solids} = (\text{Final VS}) + (\text{Fixed Solids})$$
$$= 0.2449 + 0.202$$
$$= 0.4469 \text{ kg}$$

$$\text{The Final Carbon Content} = 29.9\% \text{ of the Final Total Solids}$$
$$= (0.299)\ (0.4469)$$
$$= 0.1336 \text{ kg}$$

$$\% \text{ Carbon Reduction} = \frac{0.359 - 0.1336}{0.359}(100)$$

$$\% \text{ Carbon Reduction} = 62.8 = 63\%$$